Solar wind: propagation from 1 R_{sun} to 1 AU

R. Pinto (1), A. Rouillard (1), D. Odstrcil (2,3), L. Mays (2), E. Sanchez-Diaz (1), HELCATS and CDPP teams.

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(2) NASA GSFC, Maryland, USA
(3) GSU, Fairfax, USA

Accurate solar wind simulations

. physics based modeling, alternative to semi-empirical (WSA)
. data driving, full set of background wind properties (speed, density, etc)
. addition of catalogued CMEs to background wind (HELCATS HiGeoCAT)

Solar wind propagation to 1 AU

. full 3D modelling (ENLIL, EUFHORIA)
. 1D SW propagation

Continuous real-time forecast strategies

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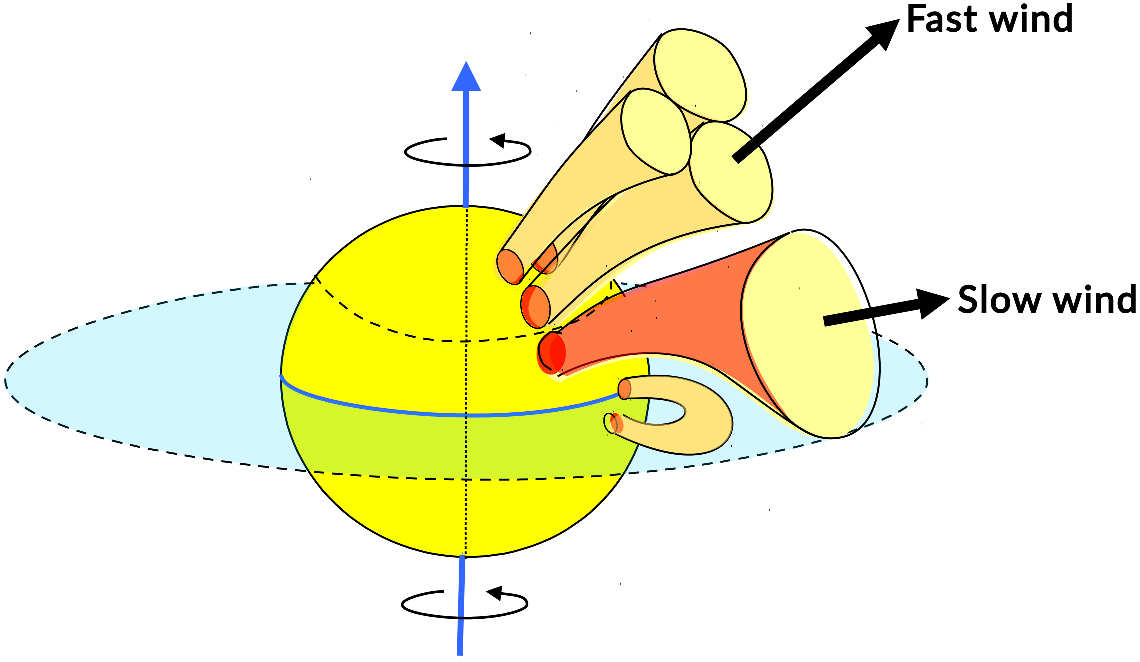
irap astrophysique & planétologie CDPP cnes CENTRE NATIONAL D'ÉTUDES SPATIALES HELCATS

http://www.helcats-fp7.eu/
http://stormsweb.irap.omp.eu

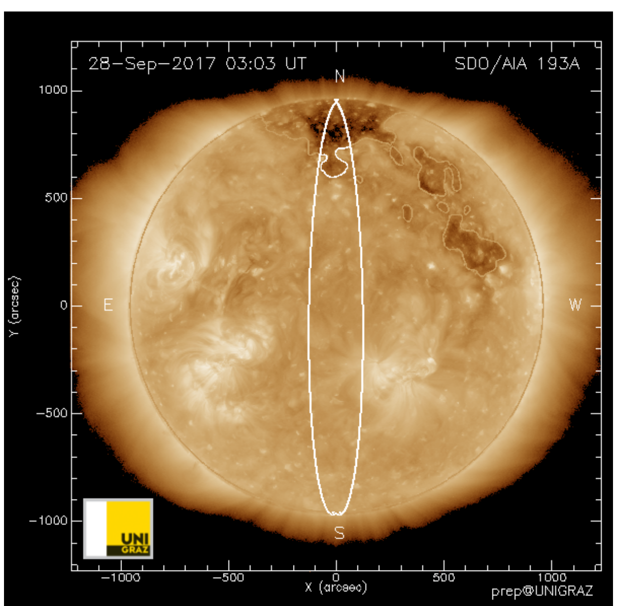
Estimating the solar wind speed



WSA semi-empirical law

$$V_{wind} = 265 + \frac{1.5}{(1+f_{ss})^{1/3}} \times \times \left[5.8 - 1.6\exp\left[1 - \frac{\theta_b{}^3}{7.5^3}\right]\right]^{3.5} \text{ km s}^{-1}$$

f_{ss}: total flux-tube expansion ratio (Wang, 1995; Velli 2013)
θ_b: distance to coronal hole boundary



(ESWF, U Graz)

CH area – speed relations

$$V = (80 \pm 2)A + 426 \pm 5.$$

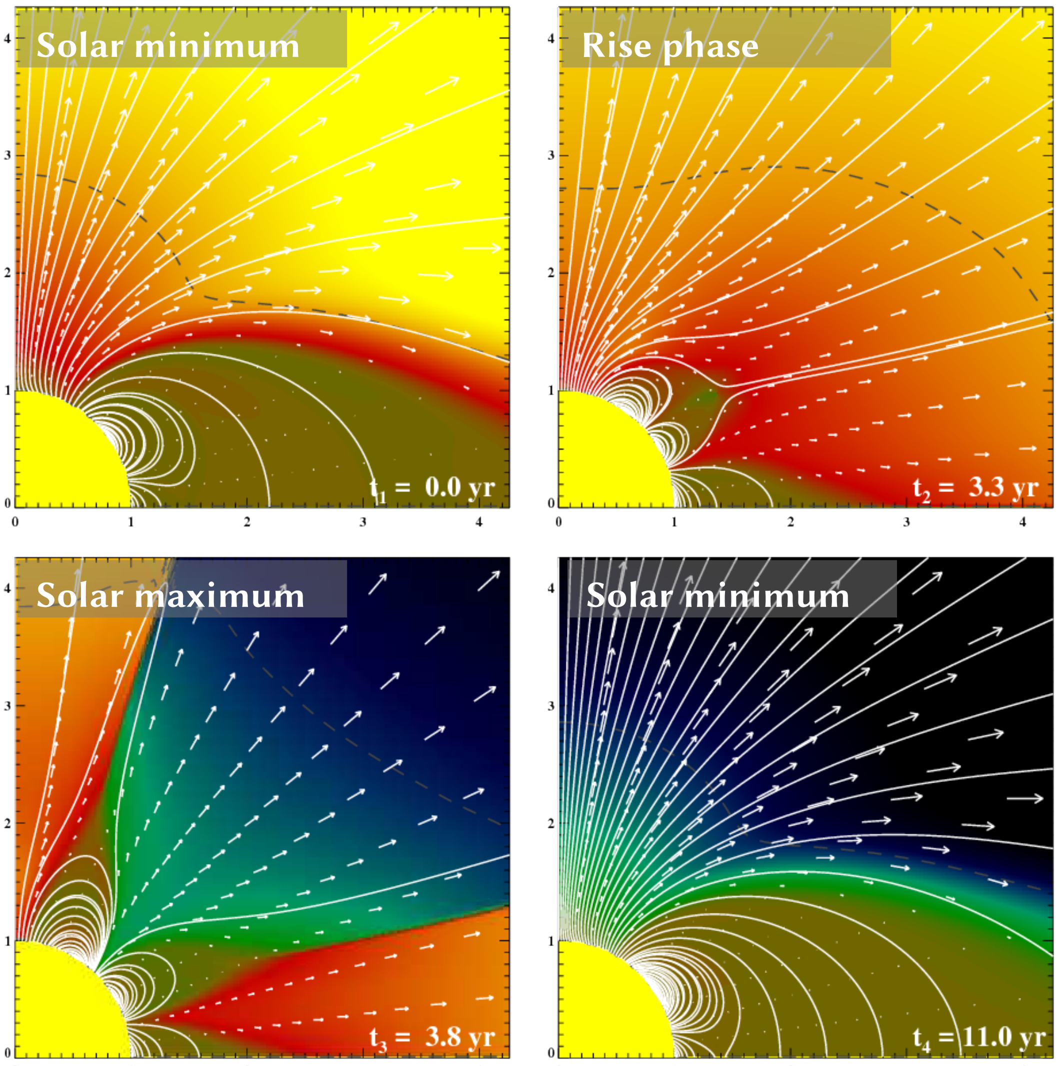
V: wind speed at 1 AU
A: total CH area

(Nolte et al 1976, Vršnak, et al 2007, Tokumaru et al 2016)

Solar wind models

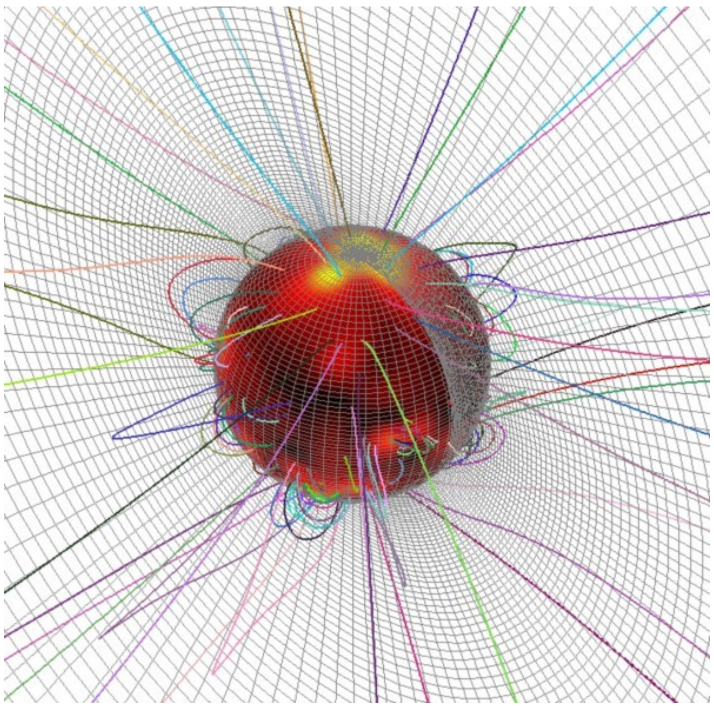
Global MHD wind models

Solar dynamo – corona – wind (11 yr cycle)



Pinto, Jouve, Grappin, Brun (2011)

Mag map based



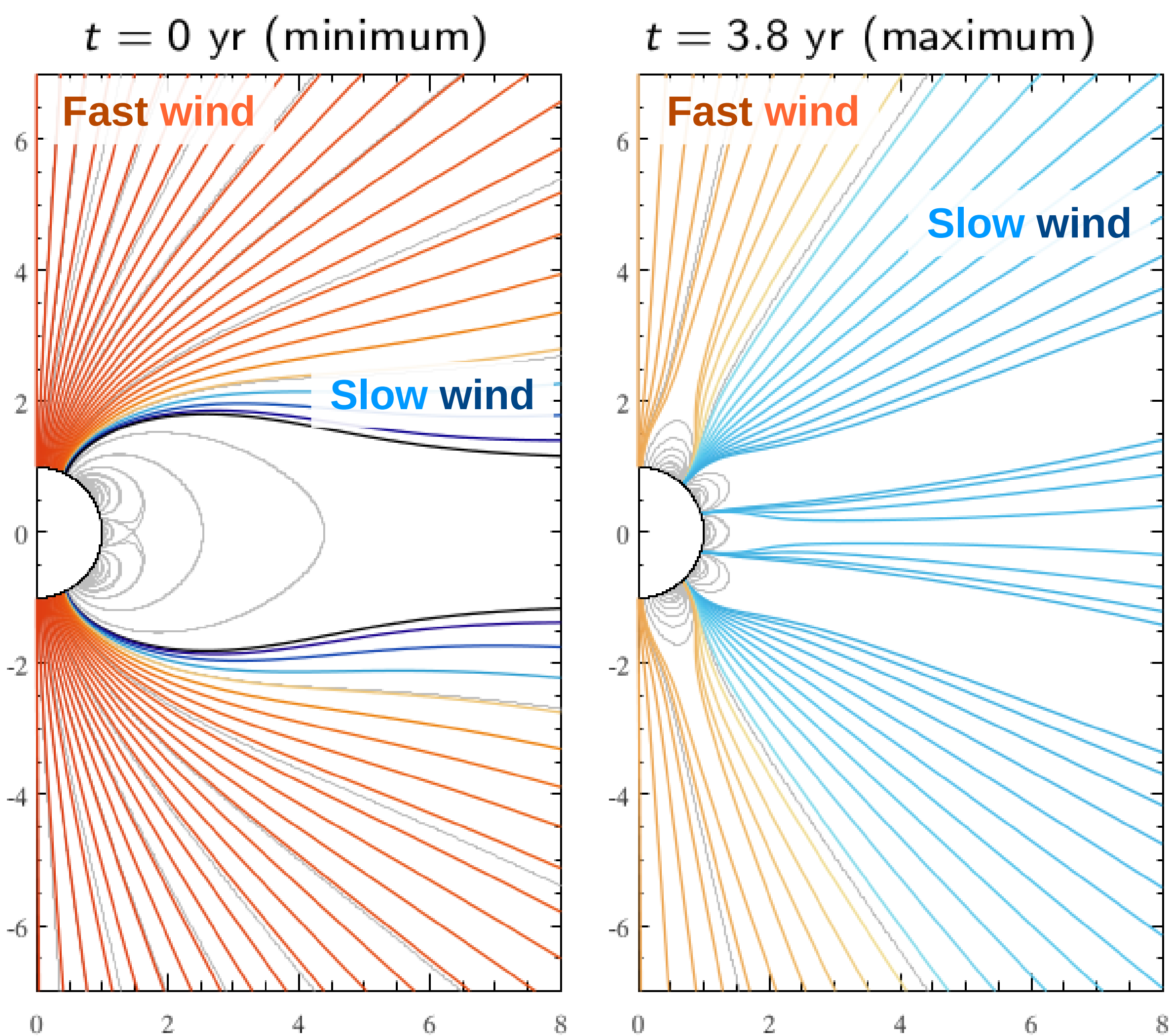
Mikić et al (2011), Riley et al (2011),
Gressl et al (2014),
van der Holst et al (2015), +

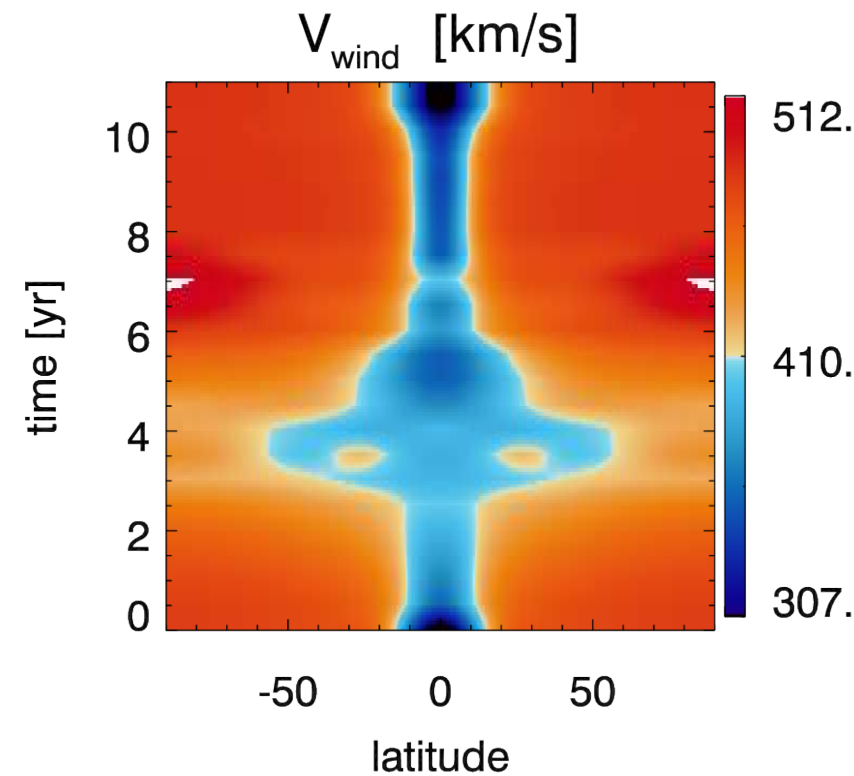
More physics, but higher complexity

Full geometry, but simplifications to thermodyn.

Solar wind speed and flux-tube geometry

Global MHD simulations of the solar dynamo, corona and solar wind (11 yr cycle)





Wind speed distribution

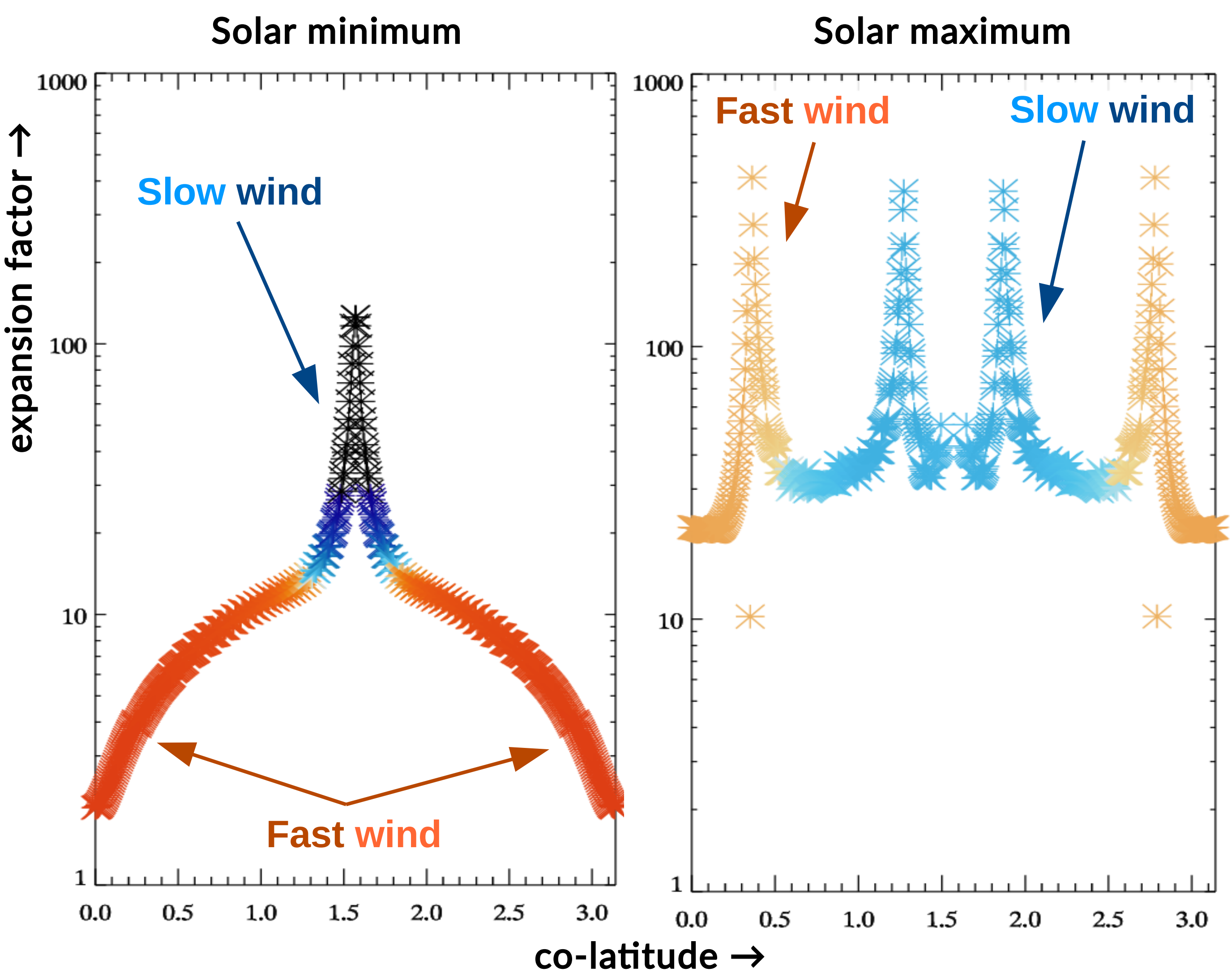
↕

Magnetic geometry

Pinto, et al (2011)
Pinto, Brun, Rouillard (2016)

Solar wind speed and flux-tube geometry

Expansion factor and wind speed



Flux-tube geometry:

- expansion profiles
- fieldline inclination

$$\partial_s v = \frac{v}{1 - M^2}\left[\frac{GM_\odot m_p}{2r^2 k_b T}\cos(\alpha) - \frac{1}{A}\partial_s A\right]$$

α: inclination angle
A: flux-tube cross-section

Pinto, Brun, Rouillard (2016)
Li, et al (2011)
Peleikis, et al (2016)

Solar wind modeling

What's missing here?

1) Theory and models

- Coronal heating (e.g, wave generation and dissipation)
- Multi-fluids, hybrid and kinetic models, heavy-ion composition
- Diagnostics (synthetic imagery, in-situ time-series)
- Propagation to 1 AU (or s/c positions)

2) SWx

- **Physics-based** modeling
- Surface to heliosphere
- **Other quantities**
  (density, dyn pressure, phase speeds)
- Add **minimal amount of complexity**
- **Real-time** modeling
  (current full 3D MHD models are very CPU intensive)

SWiFT / MULTI-VP Data-driven solar wind model

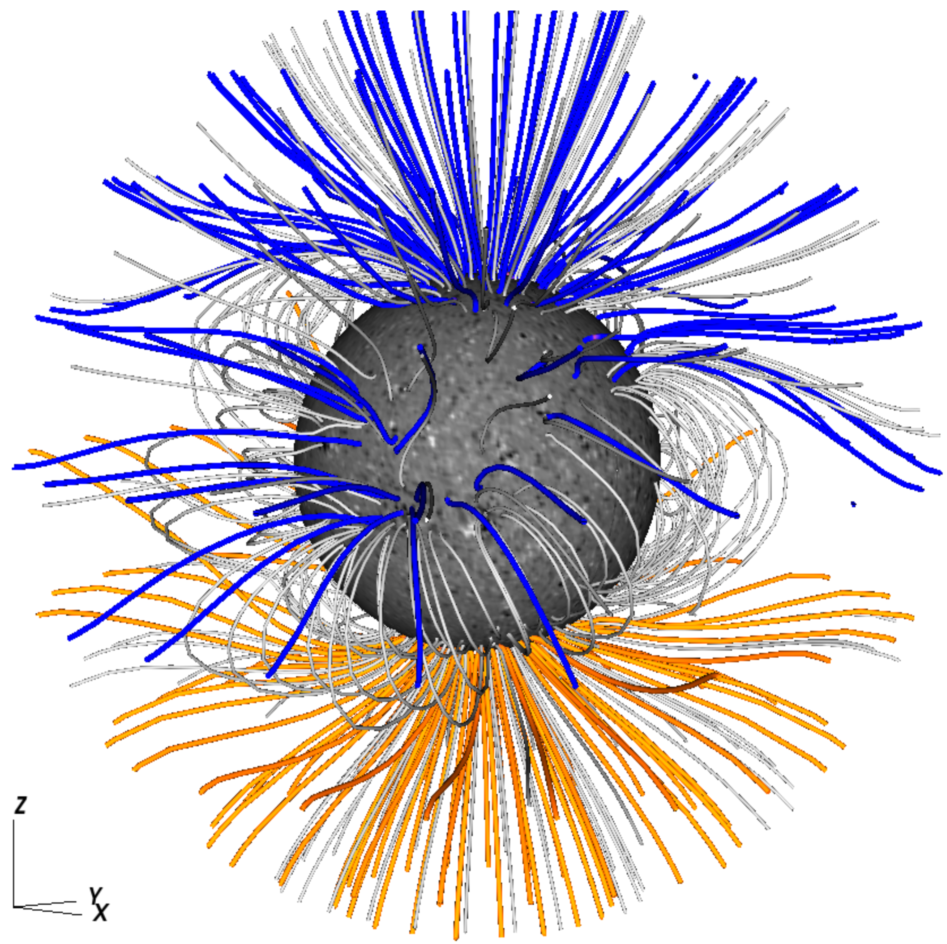
Sun / surface observations
(magnetograms: HMI, WSO, ADAPT)

Coronal field reconstruction
(PFSS, NLFFF, SolarModels)

MULTI-VP

Heliospheric propagation
(ENLIL, EUHFORIA, Tao 1D)

Earth / interplanetary medium
(S/C data, heliospheric imaging)



PFSS field lines: positive / negative polarity

SWiFT / MULTI-VP Data-driven solar wind model

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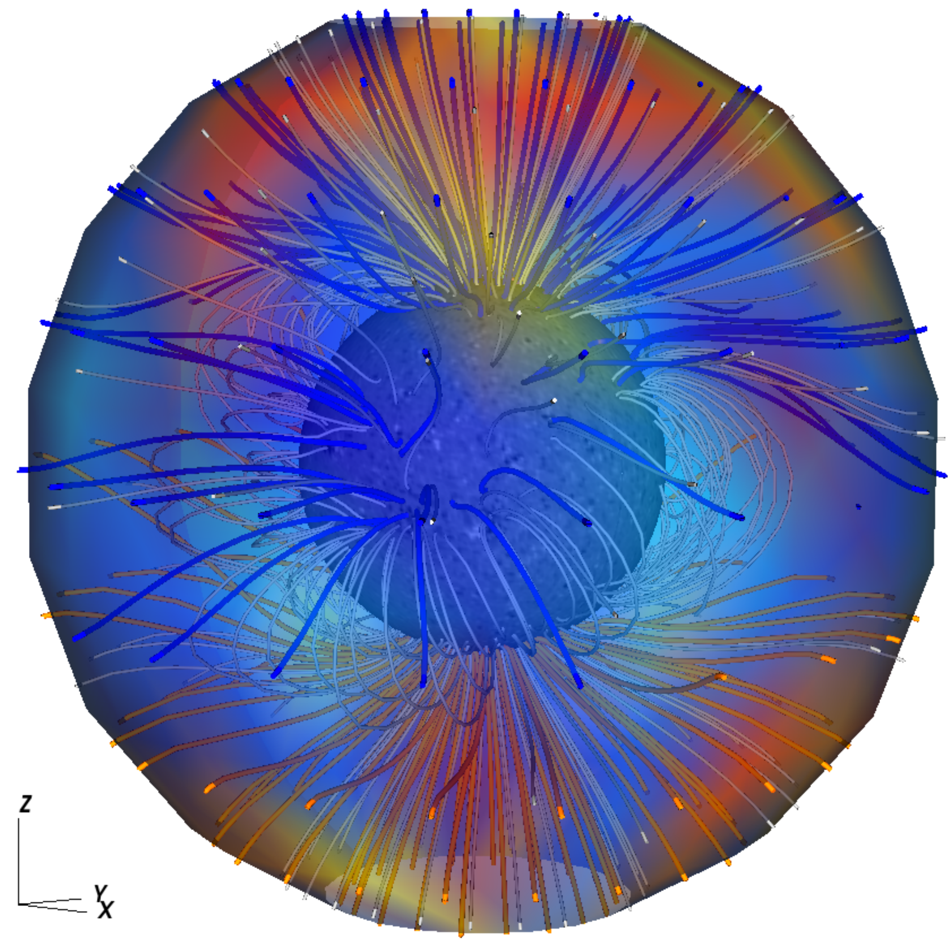
MULTI-VP

Heliospheric propagation
(ENLIL, EUHFORIA, Tao 1D)

Earth / interplanetary medium
(S/C data, heliospheric imaging)

SWiFT framework pipeline



PFSS field lines: positive / negative polarity
Wind speed: 300 / 700 km/s

MULTI-VP Data-driven solar wind model

Solar minimum

Solar maximum

PFSS magnetic field extrapolations
(but could be PFSS-+SCS, NLFFF, SolarModels, etc)

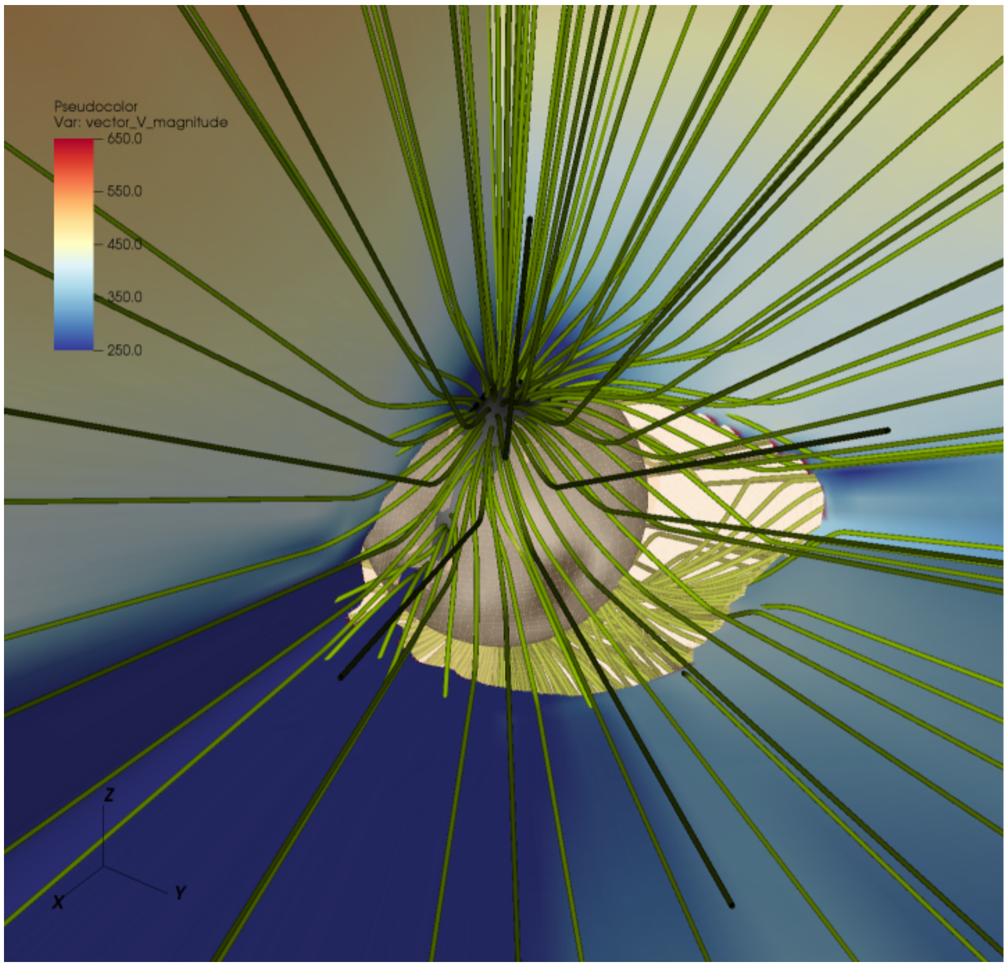
Open magnetic fieldlines ("coronal holes")
Streamer / coronal hole boundaries

Pinto, Rouillard, ApJ (2017)

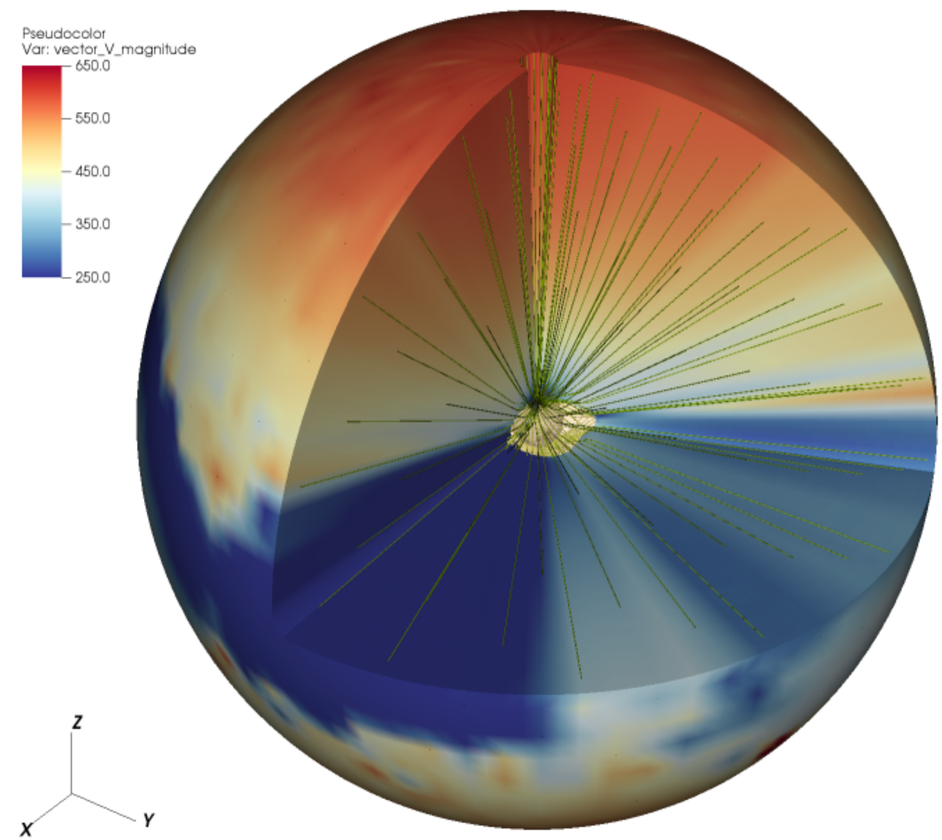
MULTI-VP Data-driven solar wind model

CR 2055

Solar wind speed



Low corona (close-up view)



High corona (1 – 15 R_{sun})

Open magnetic fieldlines ("coronal holes")
Streamer / coronal hole boundaries

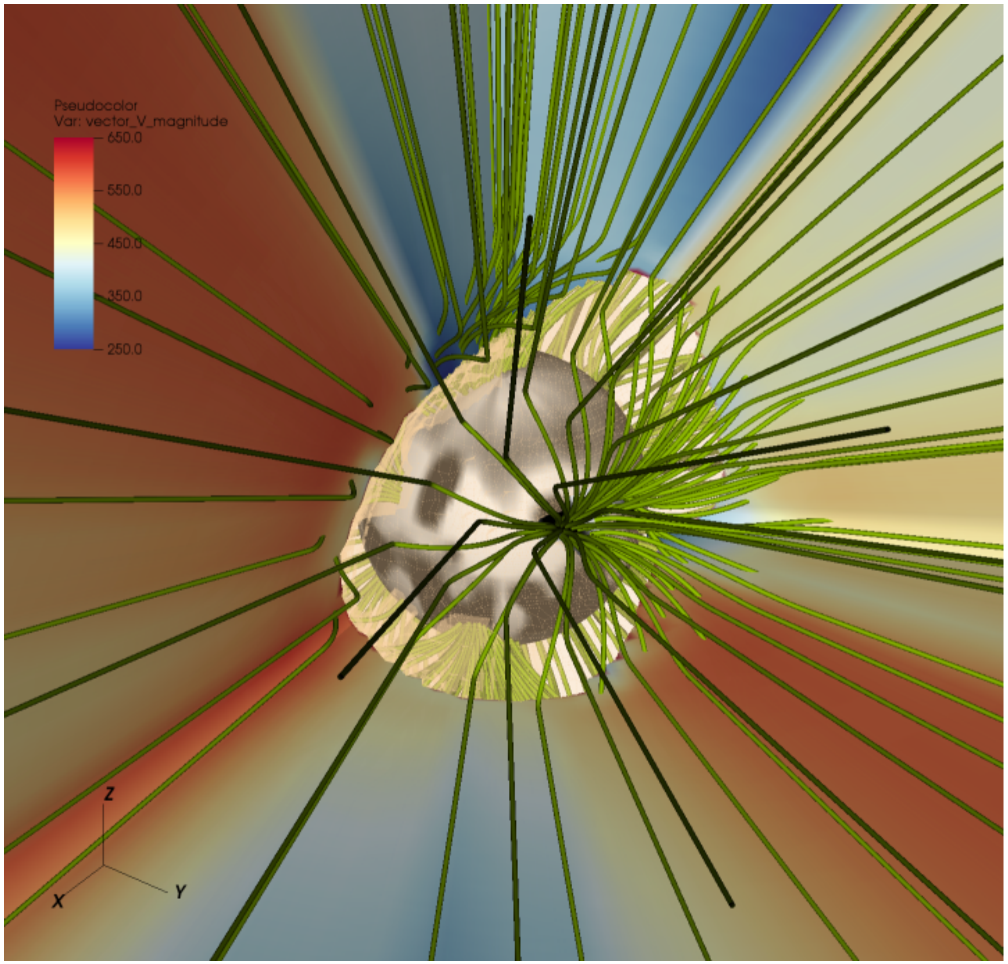
Fast wind
Slow wind

Pinto, Rouillard, ApJ (2017)

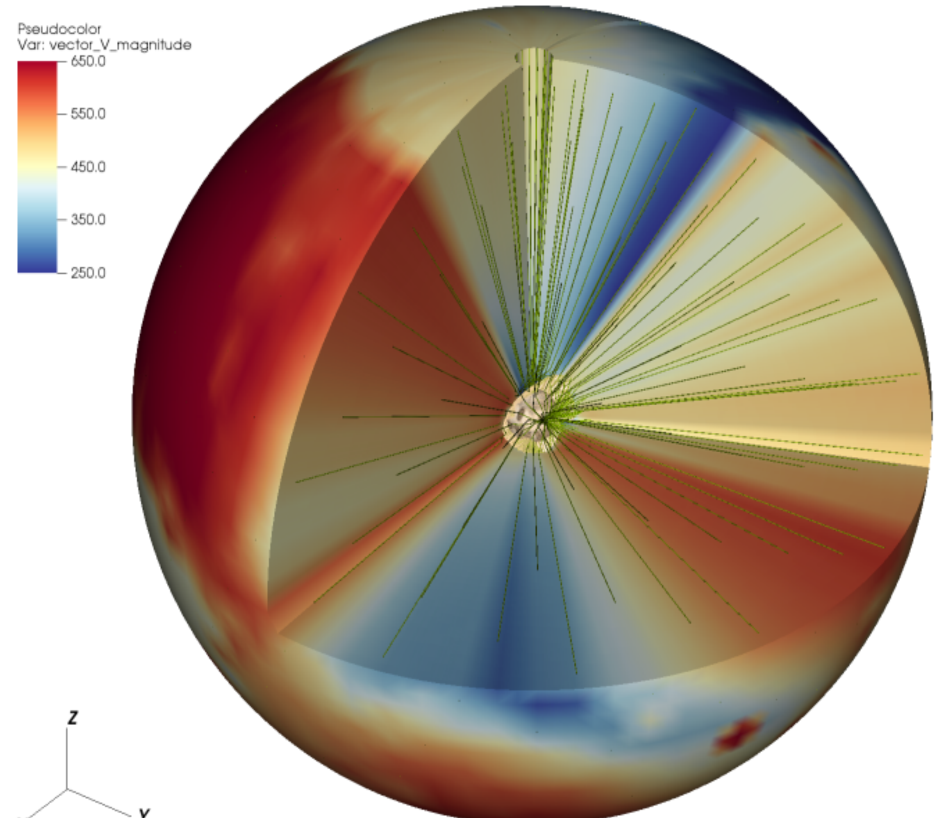
MULTI-VP Data-driven solar wind model

CR 2132

Solar wind speed



Low corona (close-up view)



High corona (1 – 15 R_{sun})

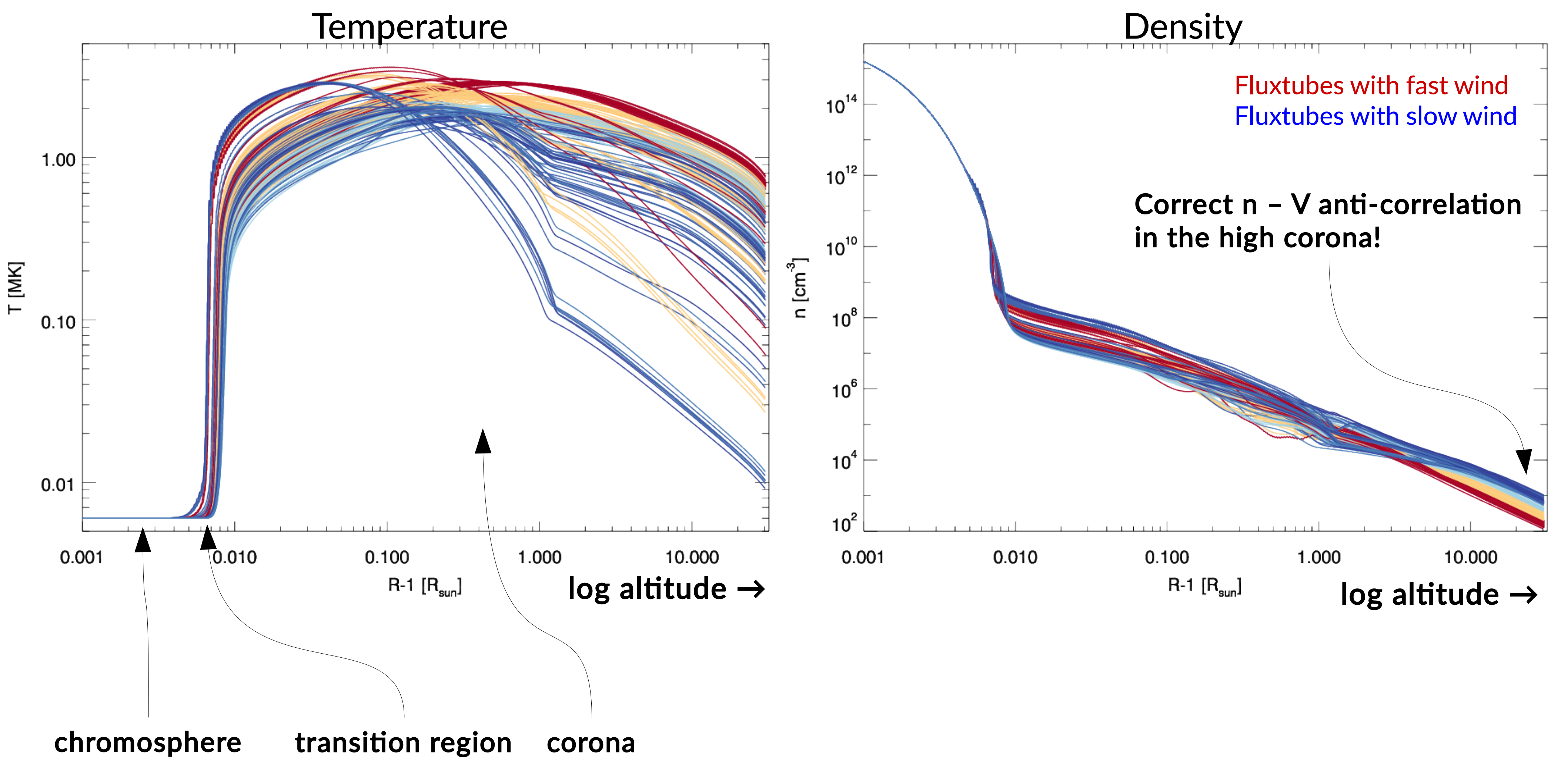
Open magnetic fieldlines ("coronal holes")
Streamer / coronal hole boundaries

Fast wind
Slow wind

Pinto, Rouillard, ApJ (2017)

MULTI-VP Data-driven solar wind model

From the surface to the corona



Pinto, Rouillard, ApJ (2017)

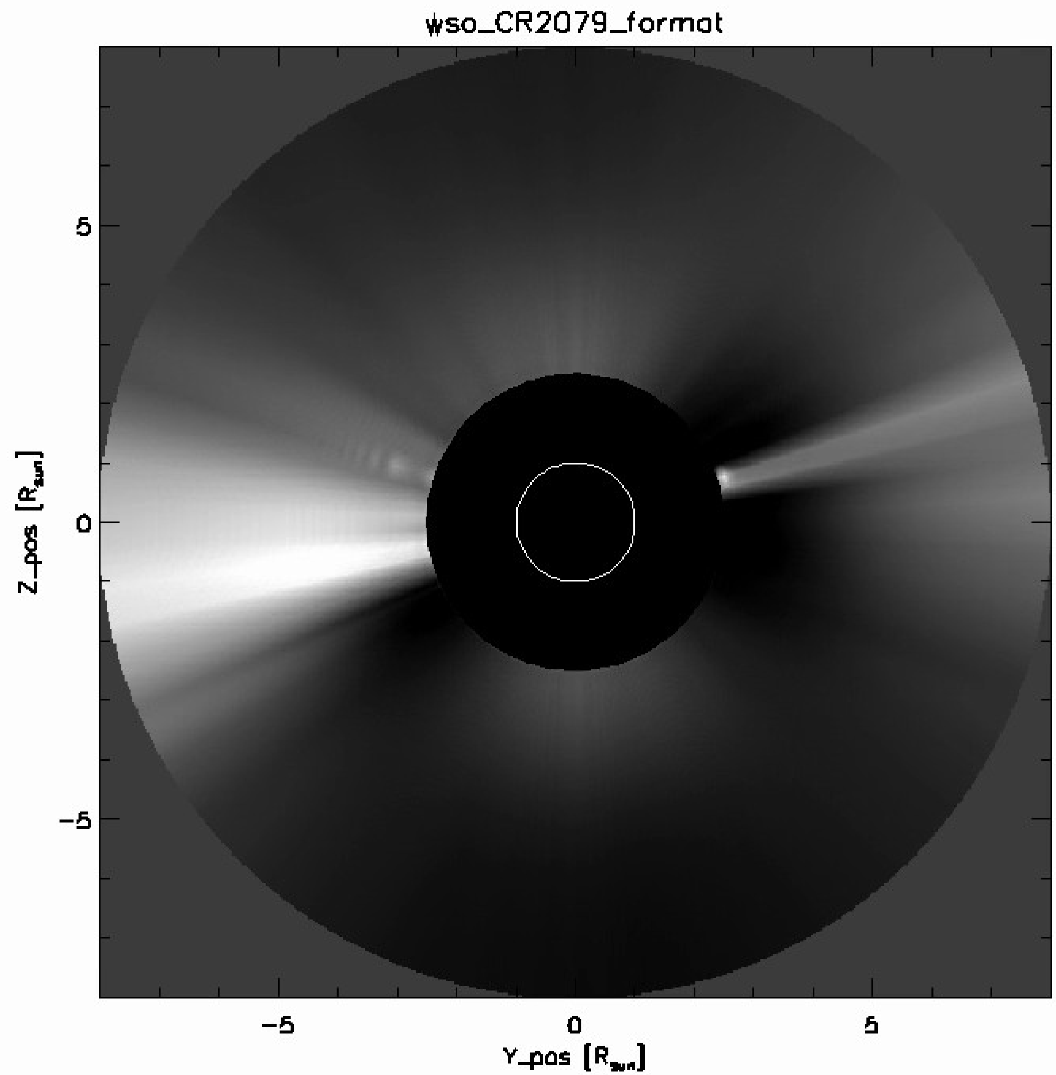
MULTI-VP Data-driven solar wind model

Synthetic images of the corona

CR 2079 – 2080

MULTI-VP + FORWARD

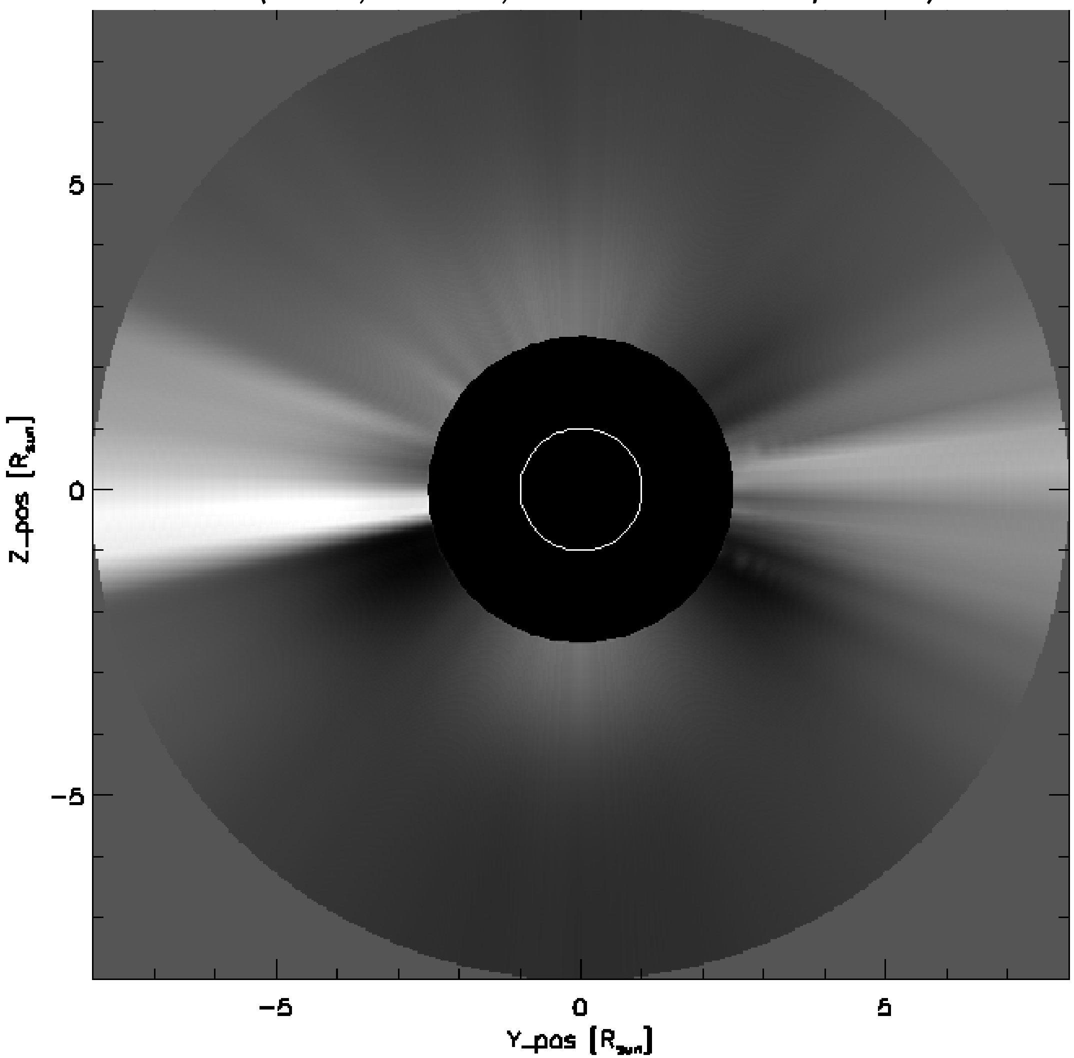
(NRGF-filtered, ~C2 FoV)



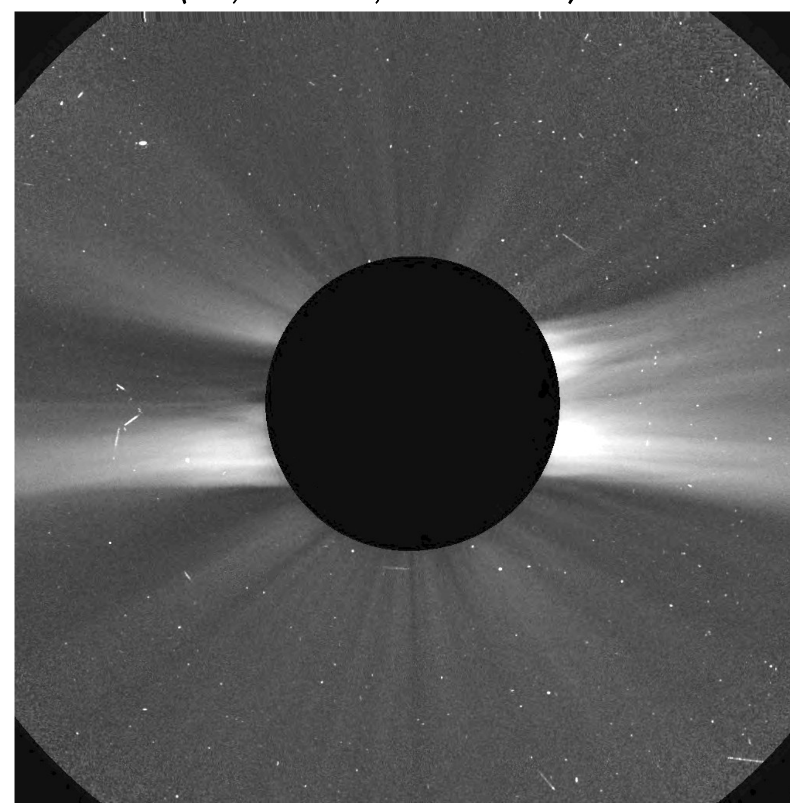
MULTI-VP Data-driven solar wind model

Synthetic images of the corona

CR 2079 (Earth, mid-CR, MULTI-VP NRGF-filtered)



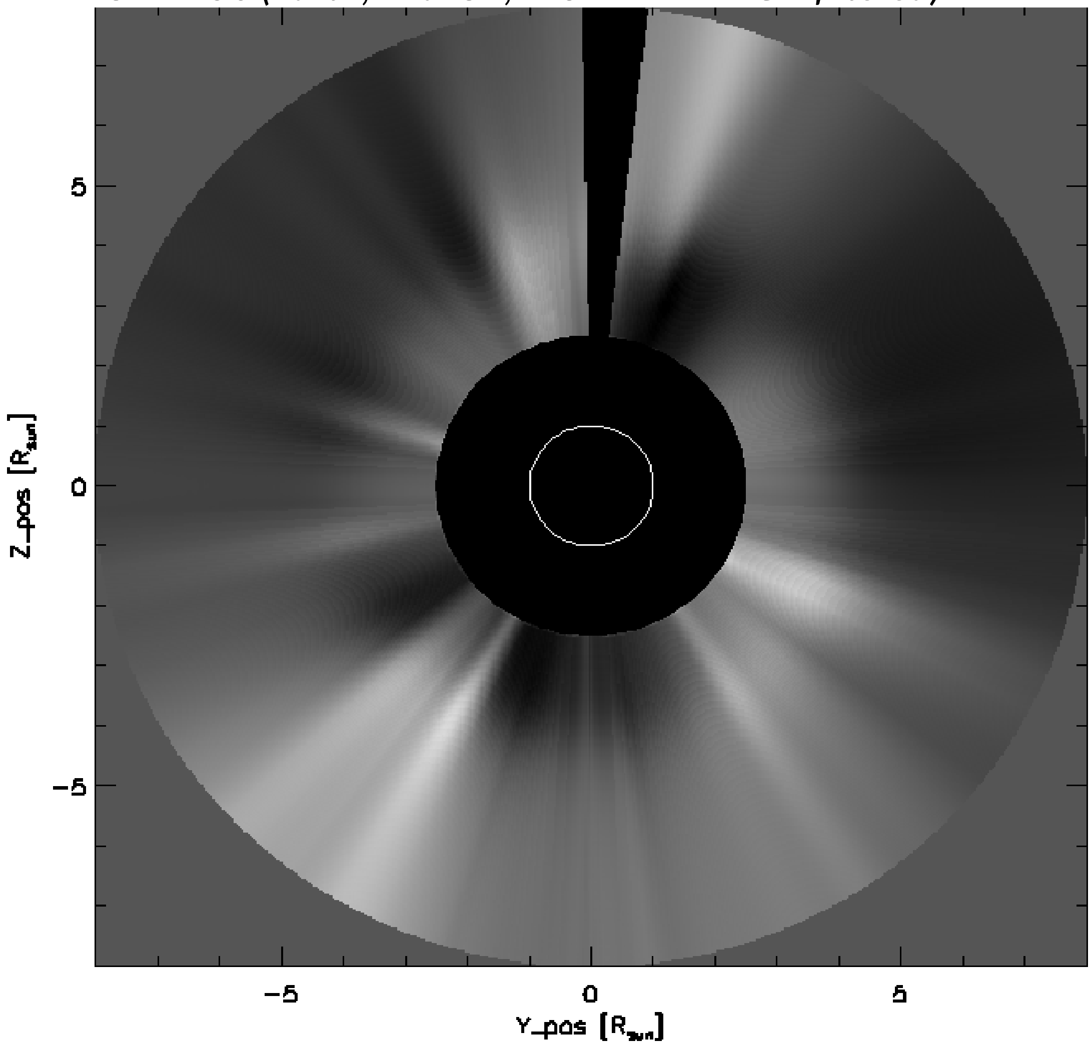
CR 2079 (L1, mid-CR, LASCO C2)



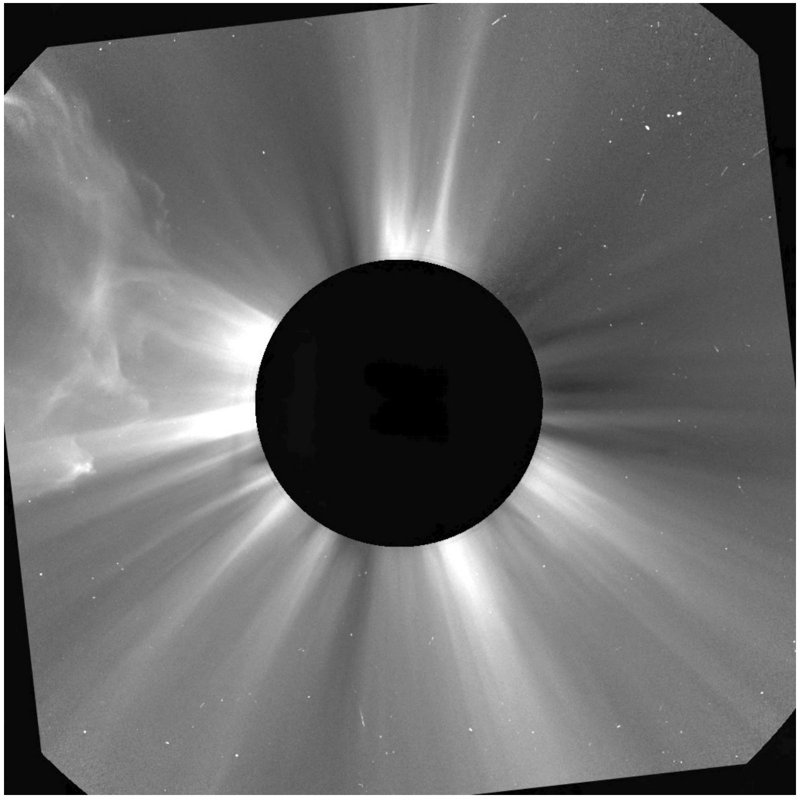
MULTI-VP Data-driven solar wind model

Synthetic images of the corona

CR 2136 (Earth, mid-CR, MULTI-VP NRGF-filtered)



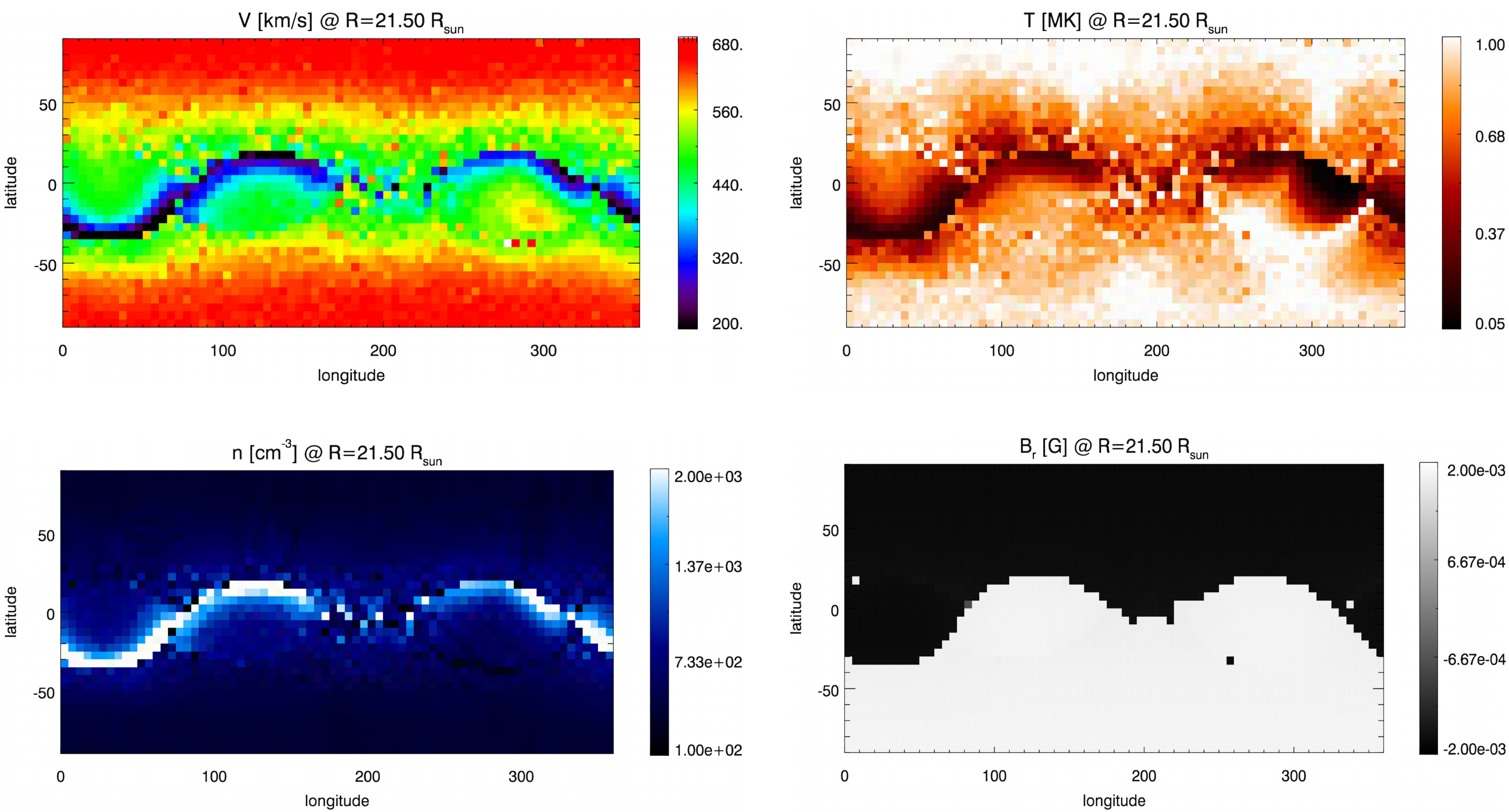
CR 2136 (L1, mid-CR, LASCO C2)



MULTI-VP Data-driven solar wind model

Solar wind maps

CR 2056 (2008, minimum)

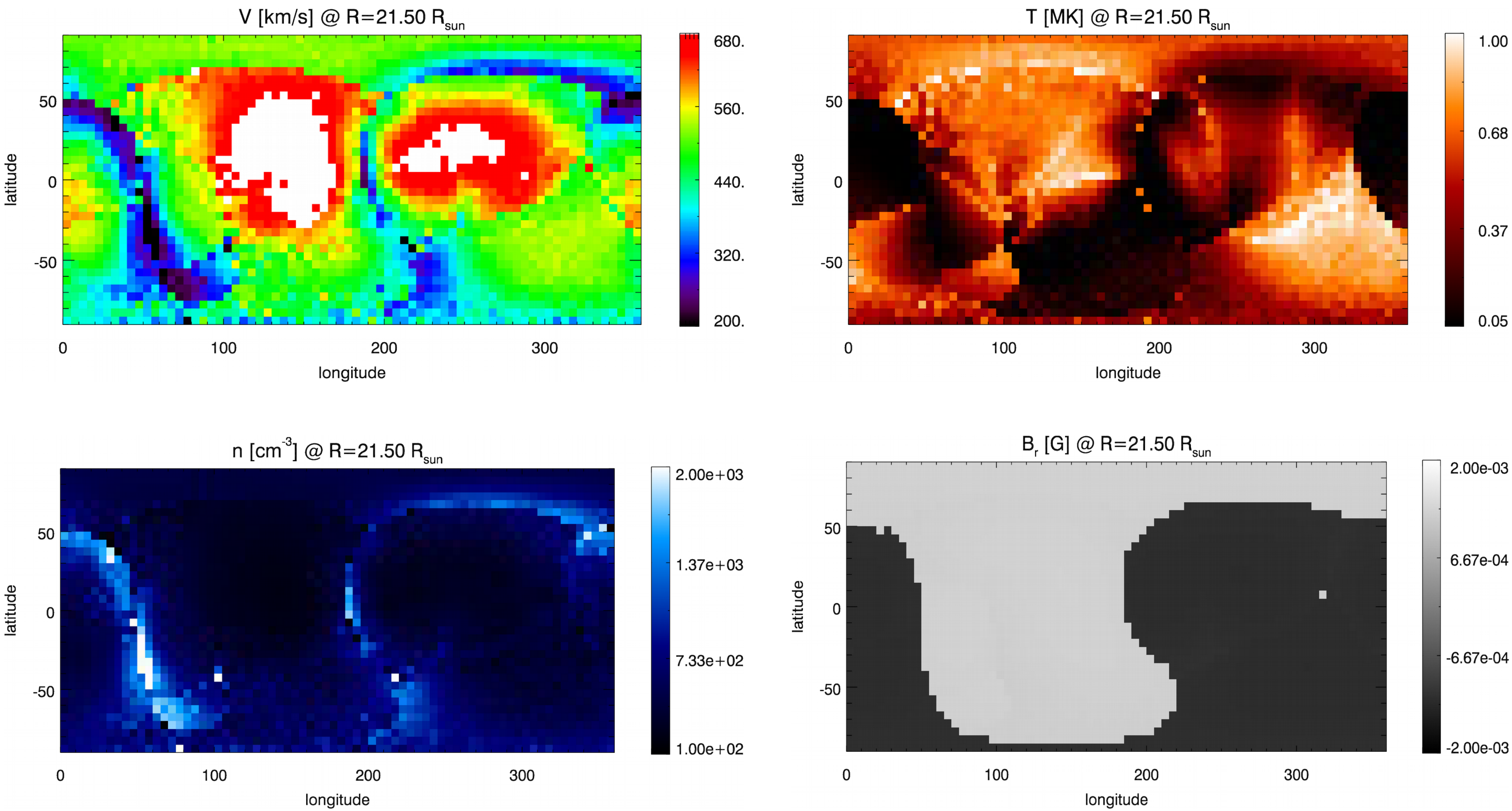


HELCATS catalogue: https://stormsweb.irap.omp.eu/doku.php?id=windmaptable

MULTI-VP Data-driven solar wind model

Solar wind maps

CR 2136 (2013, maximum)

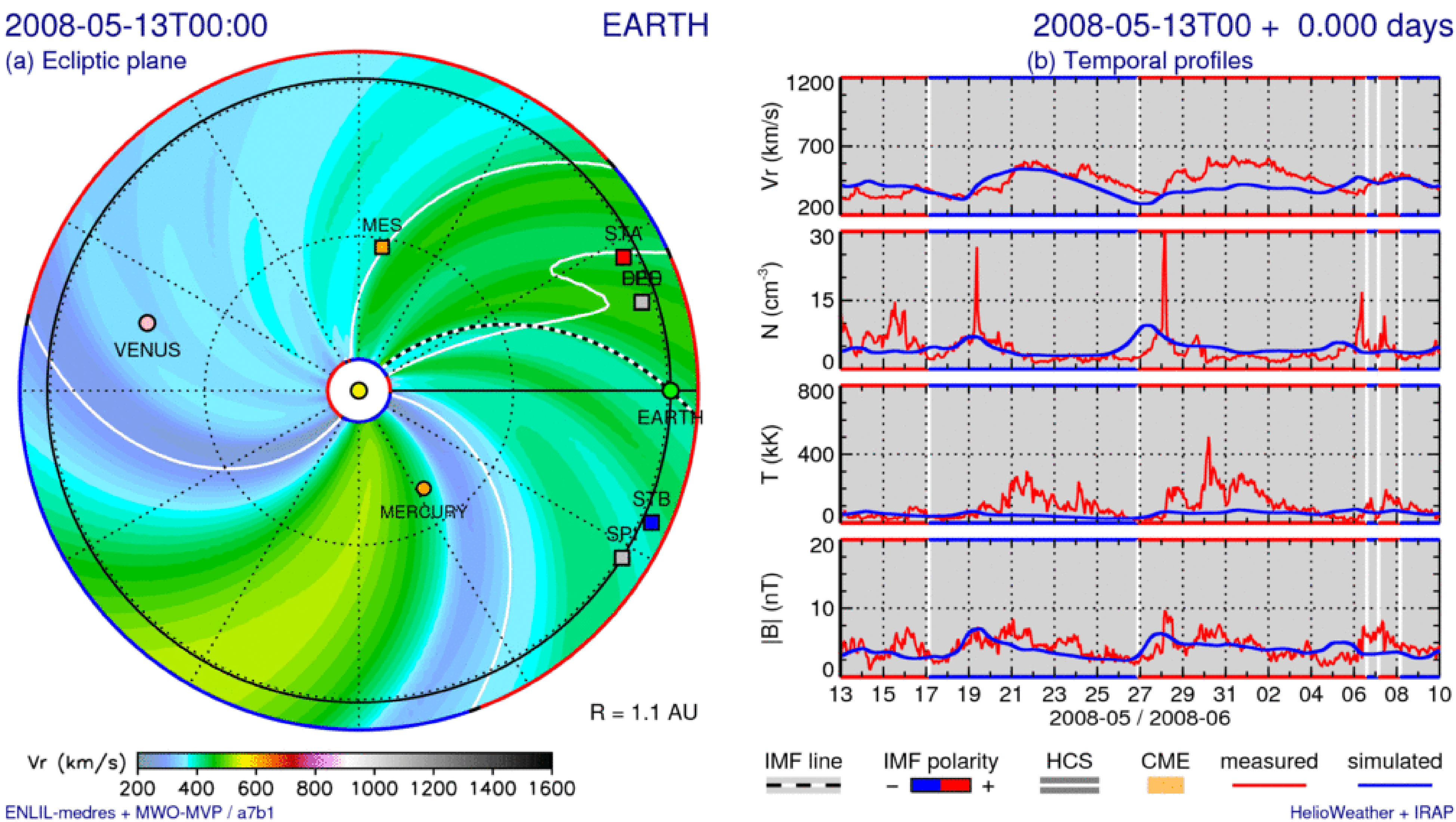


HELCATS catalogue: https://stormsweb.irap.omp.eu/doku.php?id=windmaptable

Predicting the solar wind conditions at 1 AU

Interplanetary medium, in-situ data

MULTI-VP maps at 21.5 Rsun → ENLIL

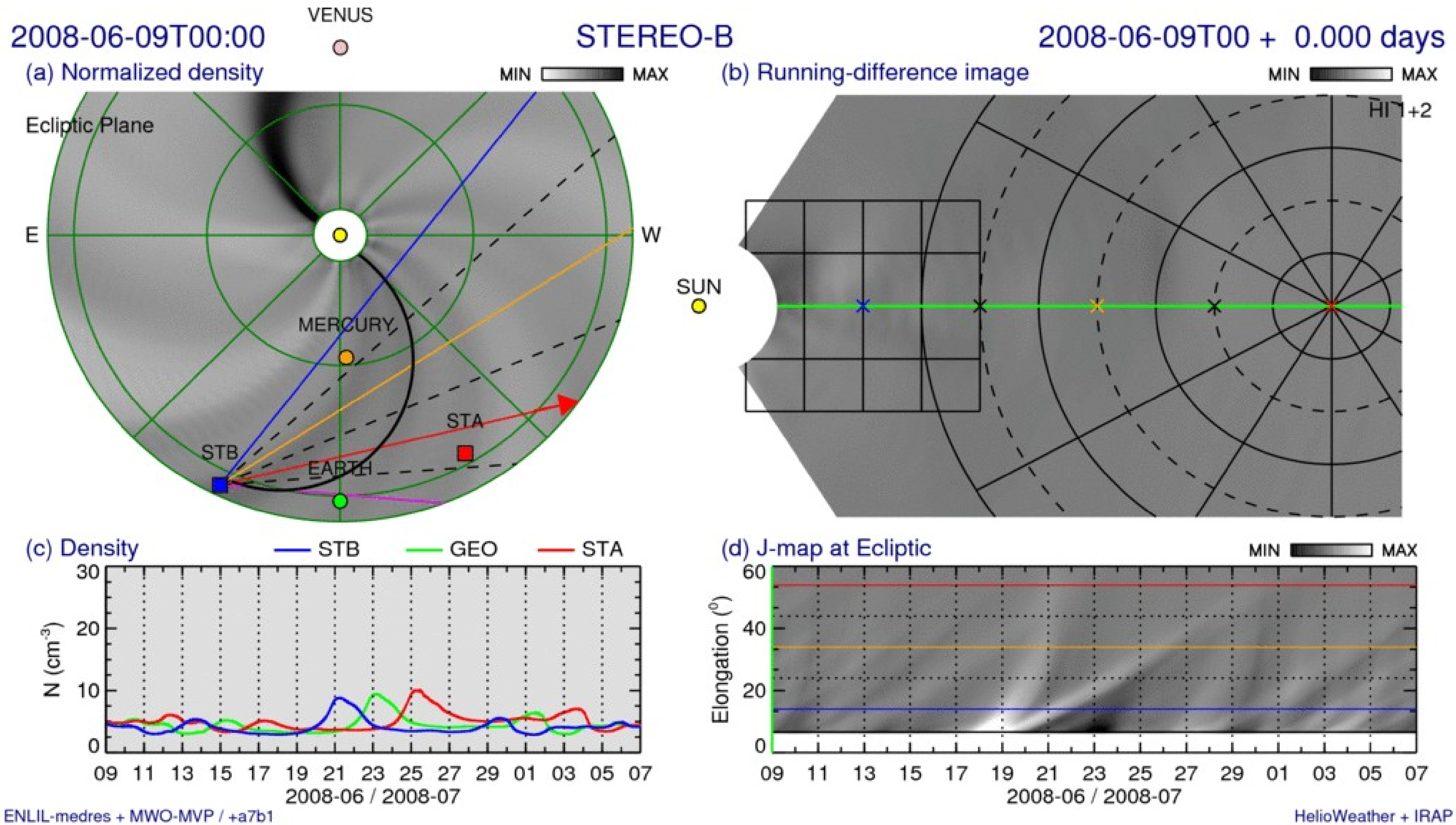


(Pinto, Rouillard, Odsctrill, Mays, et al)

http://www.helcats-fp7.eu/
http://stormsweb.irap.omp.eu

HELCATS catalogue: https://stormsweb.irap.omp.eu/doku.php?id=windmaptable

Predicting the solar wind conditions: J-maps

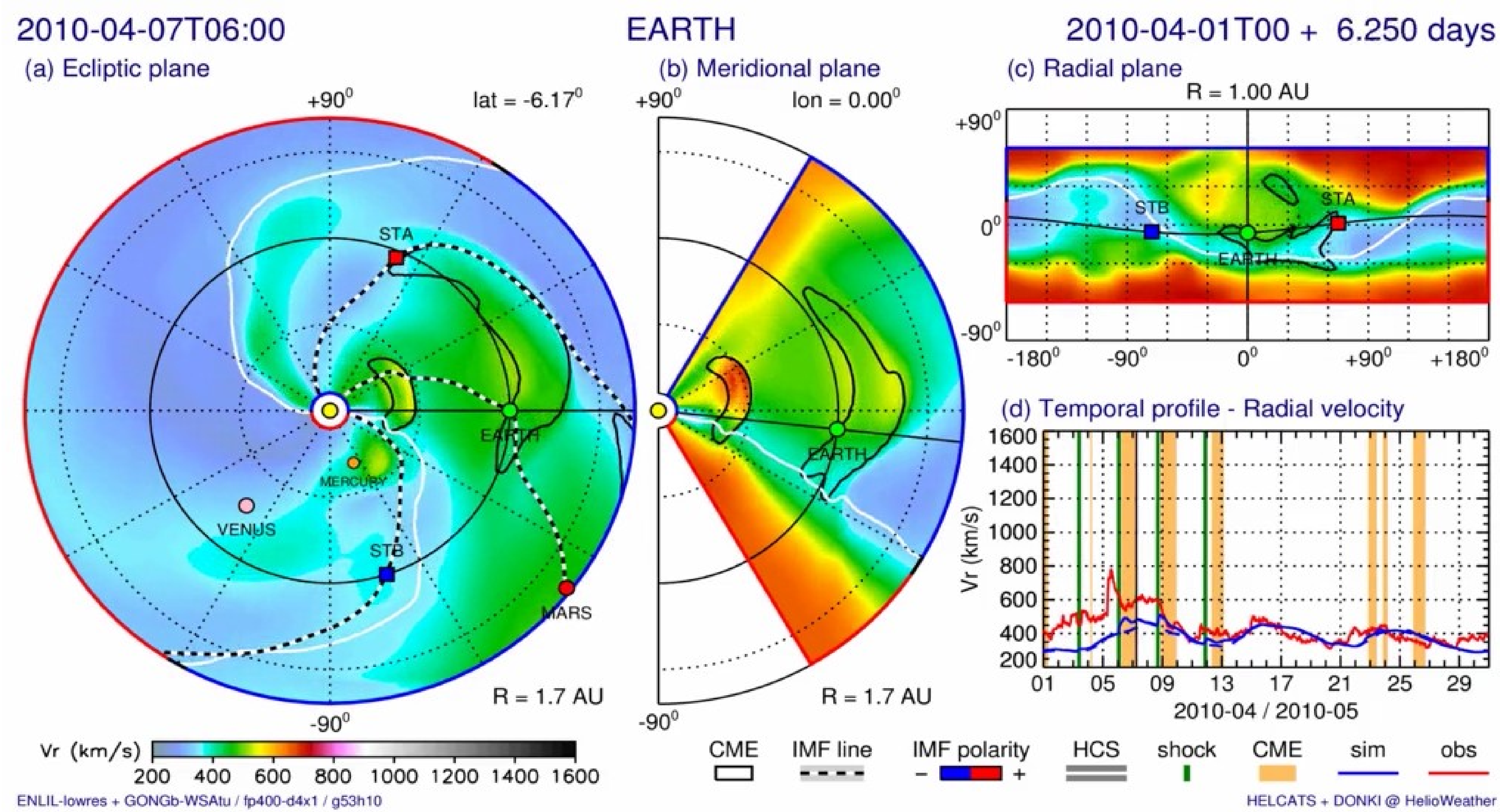


(Pinto, Rouillard, Odsctrill, Mays, et al)

http://www.helcats-fp7.eu/
http://stormsweb.irap.omp.eu

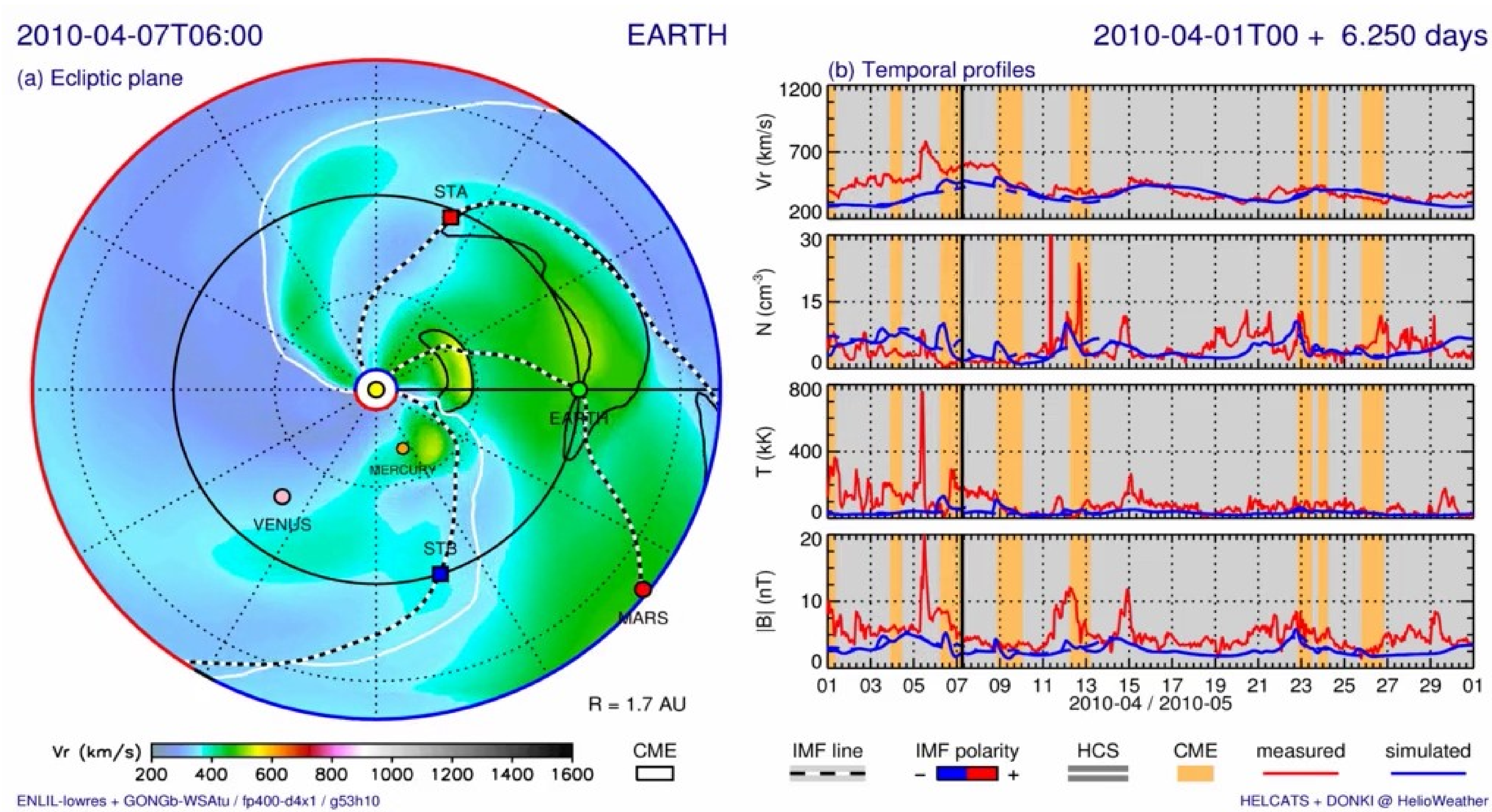
HELCATS catalogue: https://stormsweb.irap.omp.eu/doku.php?id=windmaptable

ENLIL simulations (solar wind and CMEs)



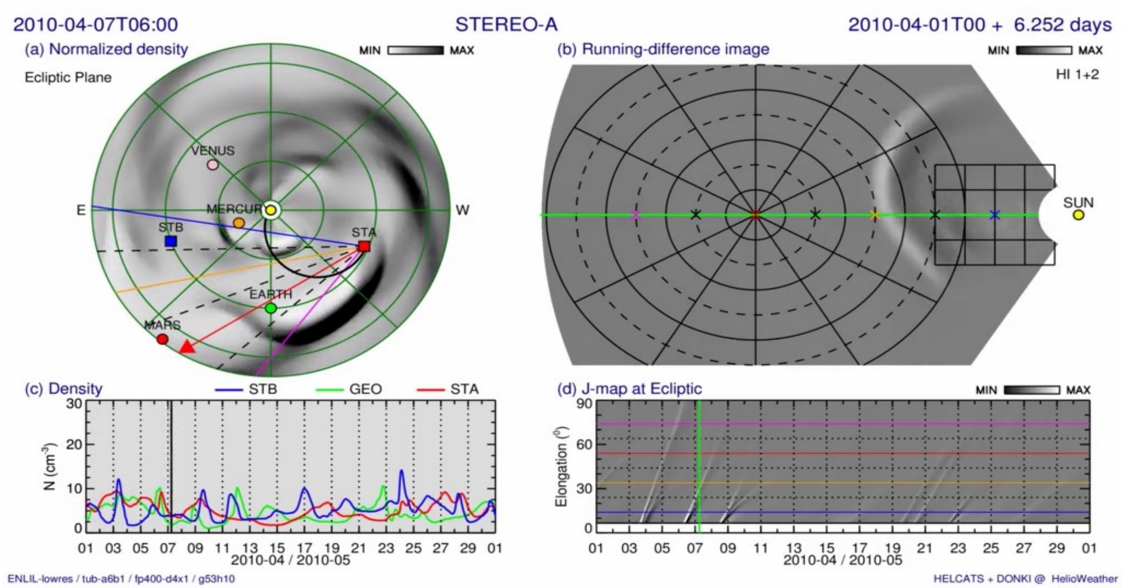
Lavarra, Rouillard, Odsctrill, Mays, et al

ENLIL simulations (solar wind and CMEs)

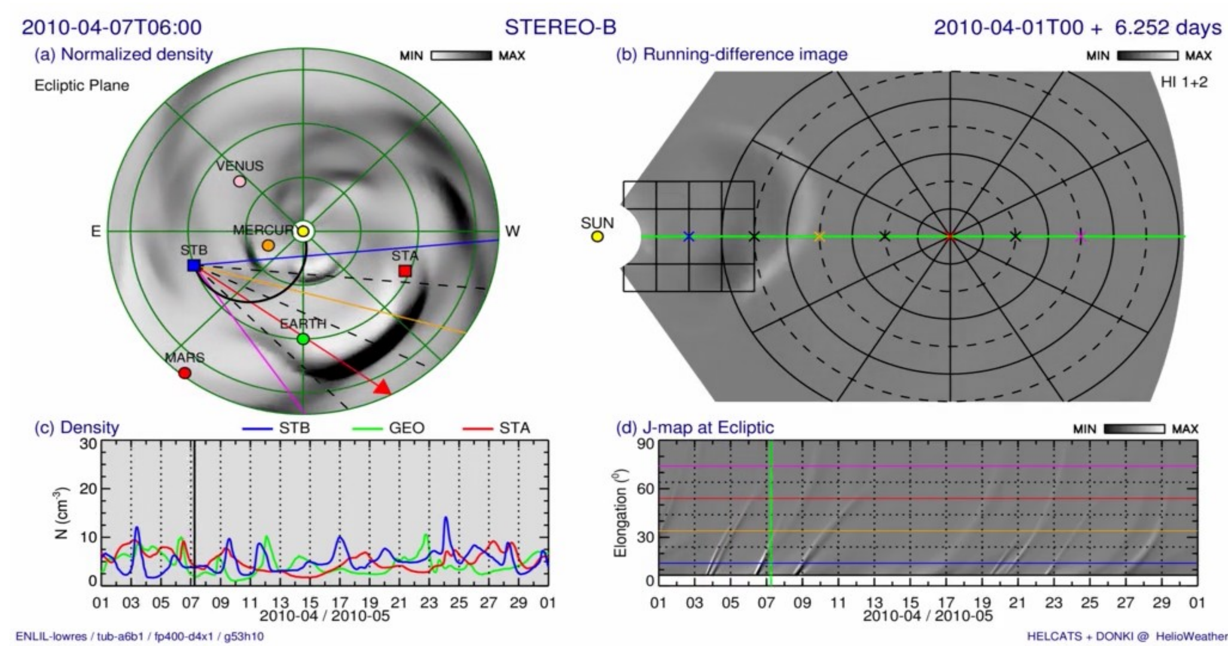


Lavarra, Rouillard, Odsctrill, Mays, et al

ENLIL simulations (solar wind and CMEs)



Synthetic HI, Jmaps
STEREO-A/B

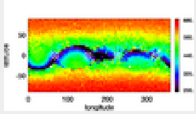
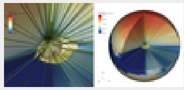
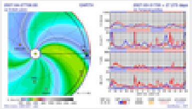
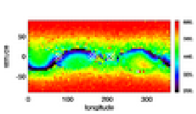
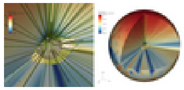
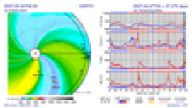
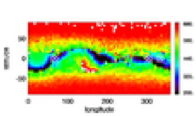
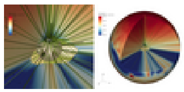
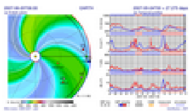
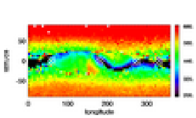
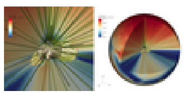
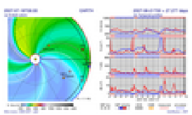
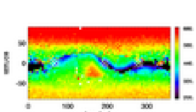
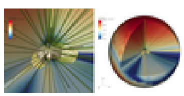
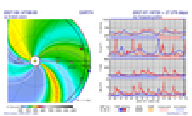
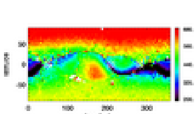
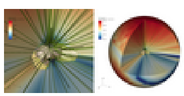
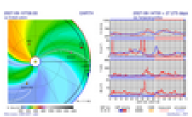
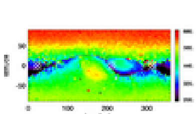
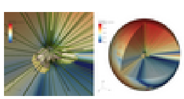
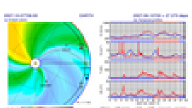


Catalogue

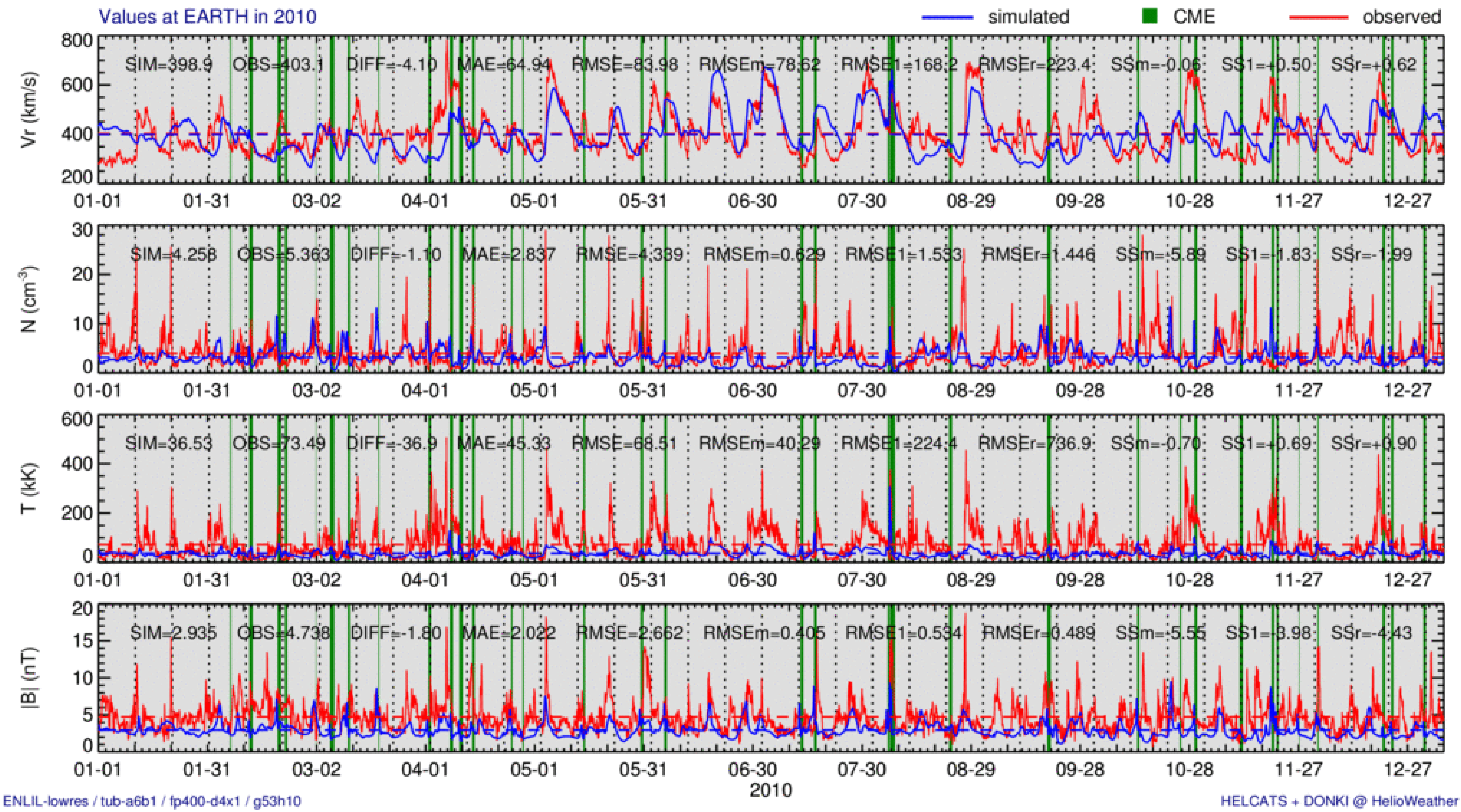
https://stormsweb.irap.omp.eu/doku.php?id=windmaptable

Solar wind maps computed using MULTI-VP+ENLIL for HELCATS

HELCATS project.
MULTI-VP runs computed at CALMIP.

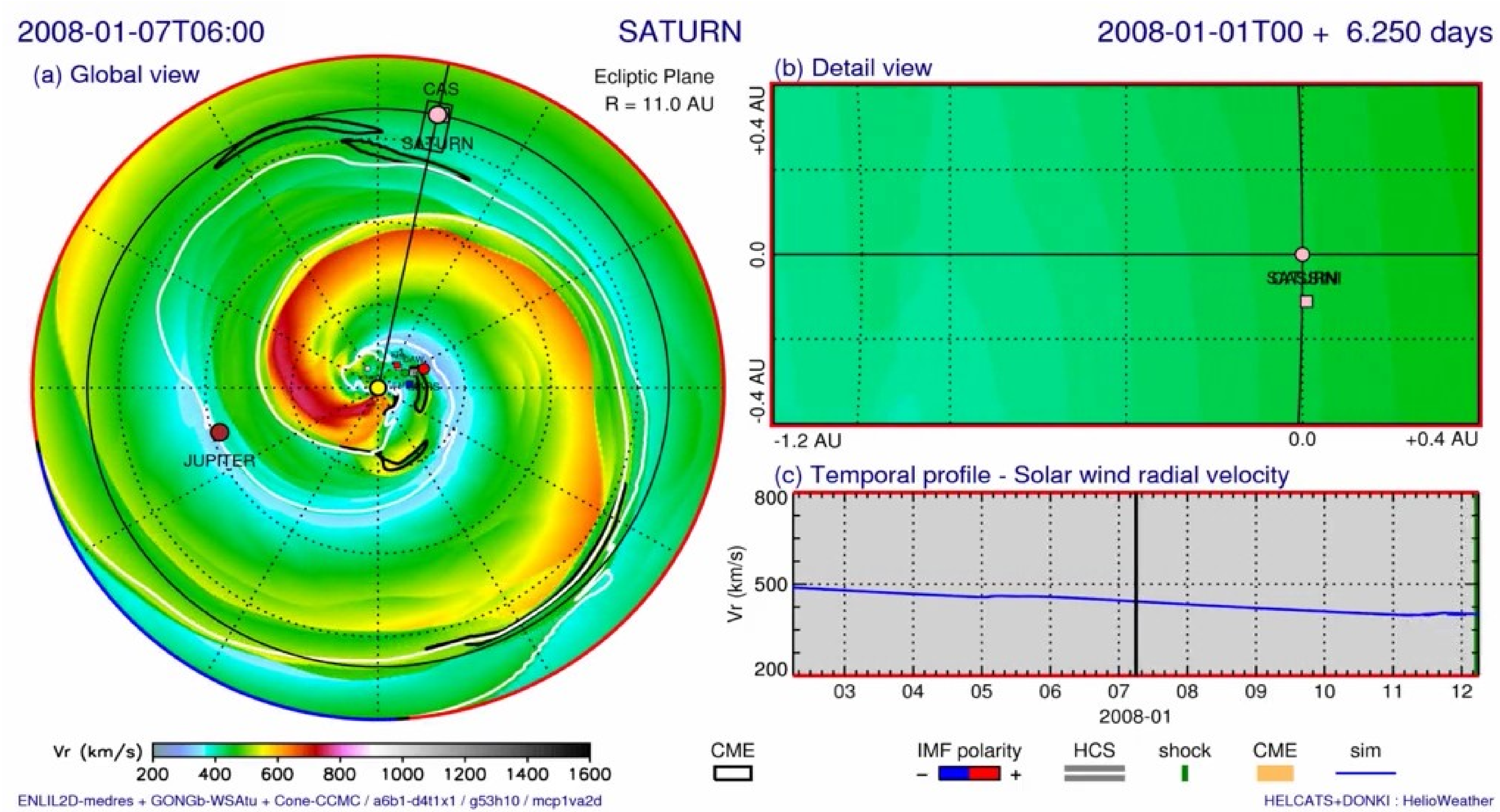
CR number	file	comments notes	quick view (V_r at 21.5 R_{sun}) caption	V_r 1-15 R_{sun}	ENLIL preview caption
CR 2055	mvp2enlil_wso_cr2055.tar.gz	wso, hc+fhc2			
CR 2056	mvp2enlil_wso_cr2056.tar.gz	wso, hc+fhc2			
CR 2057	mvp2enlil_wso_cr2057.tar.gz	wso, hc+fhc2			
CR 2058	mvp2enlil_wso_cr2058.tar.gz	wso, hc+fhc2			
CR 2059	mvp2enlil_wso_cr2059.tar.gz	wso, hc+fhc2			
CR 2060	mvp2enlil_wso_cr2060.tar.gz	wso, hc+fhc			
CR 2061	mvp2enlil_wso_cr2061.tar.gz	wso, hc+fhc			

ENLIL simulations (solar wind and CMEs)



Lavarra, Rouillard, Odsctrill, Mays, et al

ENLIL simulations (solar wind and CMEs)



Solar wind catalogues

SIMCAT catalogues

Official HELCATS website:
https://www.helcats-fp7.eu/ (under WP6 dataproducts)

MULTI-VP background solar wind simulations:
https://stormsweb.irap.omp.eu/doku.php?id=windmaptable

Combined background solar wind HELCATS-DONKI CME catalogues (CMEs > 400 km/s):
http://helioweather.net/archive/

Combined background solar wind with HELCATS-DONKI CME catalogues (all speeds):
https://ccmc.gsfc.nasa.gov/community/HELCATS/

Pinto, R., Brun A.S., Rouillard, A.P., Flux-tube geometry and solar wind speed during an activity cycle, Astronomy & Astrophysics, 592, 11, 2016
Pinto, R., Rouillard, A.P., A Multiple Flux-tube Solar Wind Model, The Astrophysical Journal, 838, 2, 89, 15, 2017
Pinto, R., Rouillard, A.P., Odstrcil, D., Mays, L., Global simulations of the solar wind and Coronal Mass Ejections during a solar cycle, ApJ, In preparation 2017.
Rouillard, A.P., Lavraud, B., Génot, V., et al., A propagation tool to connect remote-sensing observations with in-situ measurements of heliospheric structures
Lavarra, M., Rouillard, A.P., Mays, L., Odstrcil, D., Assimilating heliospheric images in global simulations of CME to improve forecasting capabilities, in prep., 2017

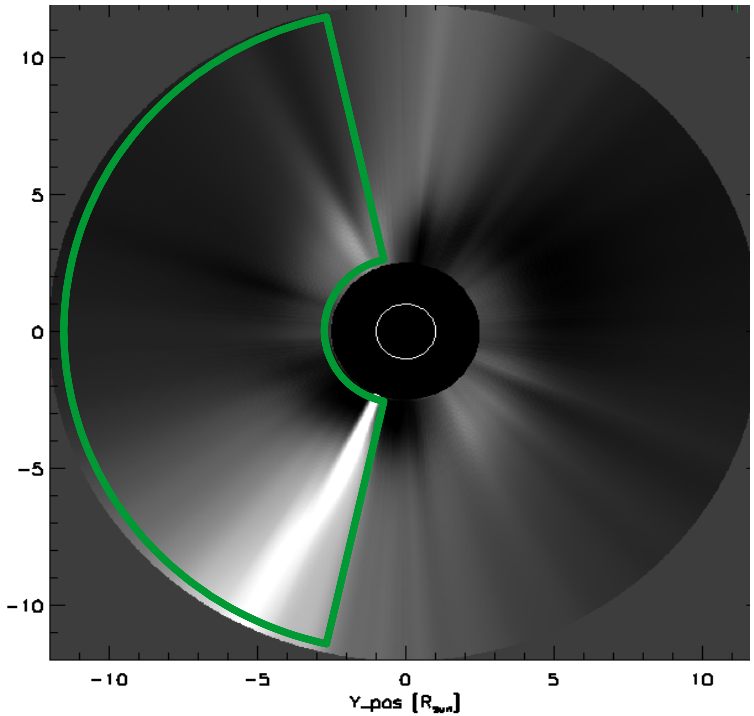
WIP: Continuous solar wind forecast (7-10 days ahead)

1. Early-on magnetogram data

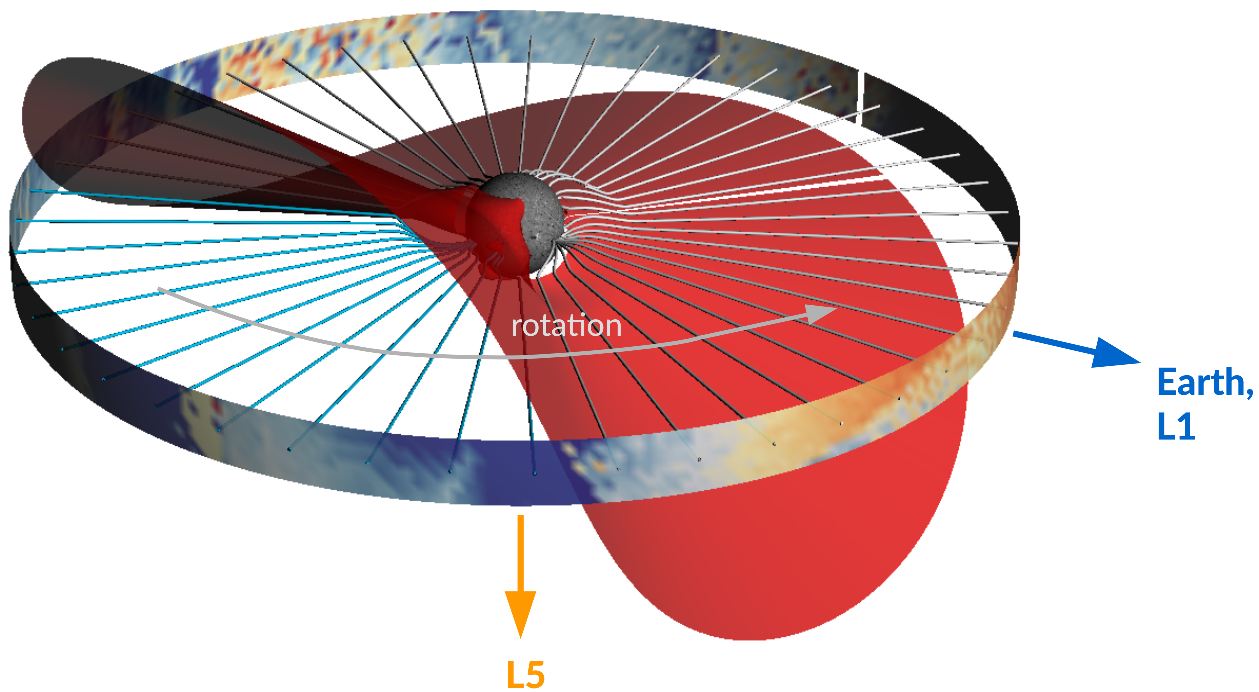
2. East-limb nowcast
synthetic vs. real coronographic imagery
calibration, re-iteration, forecast quality flags

3. L5 in-situ cross-check
verify and (re-)flag propagated wind solutions

4. Sun-Earth path on west limb
real-time monitoring, Cor/HI imaging



East limb nowcast
(synthetic coron. imaging)



SWiFT pipeline
L1+L5 missions

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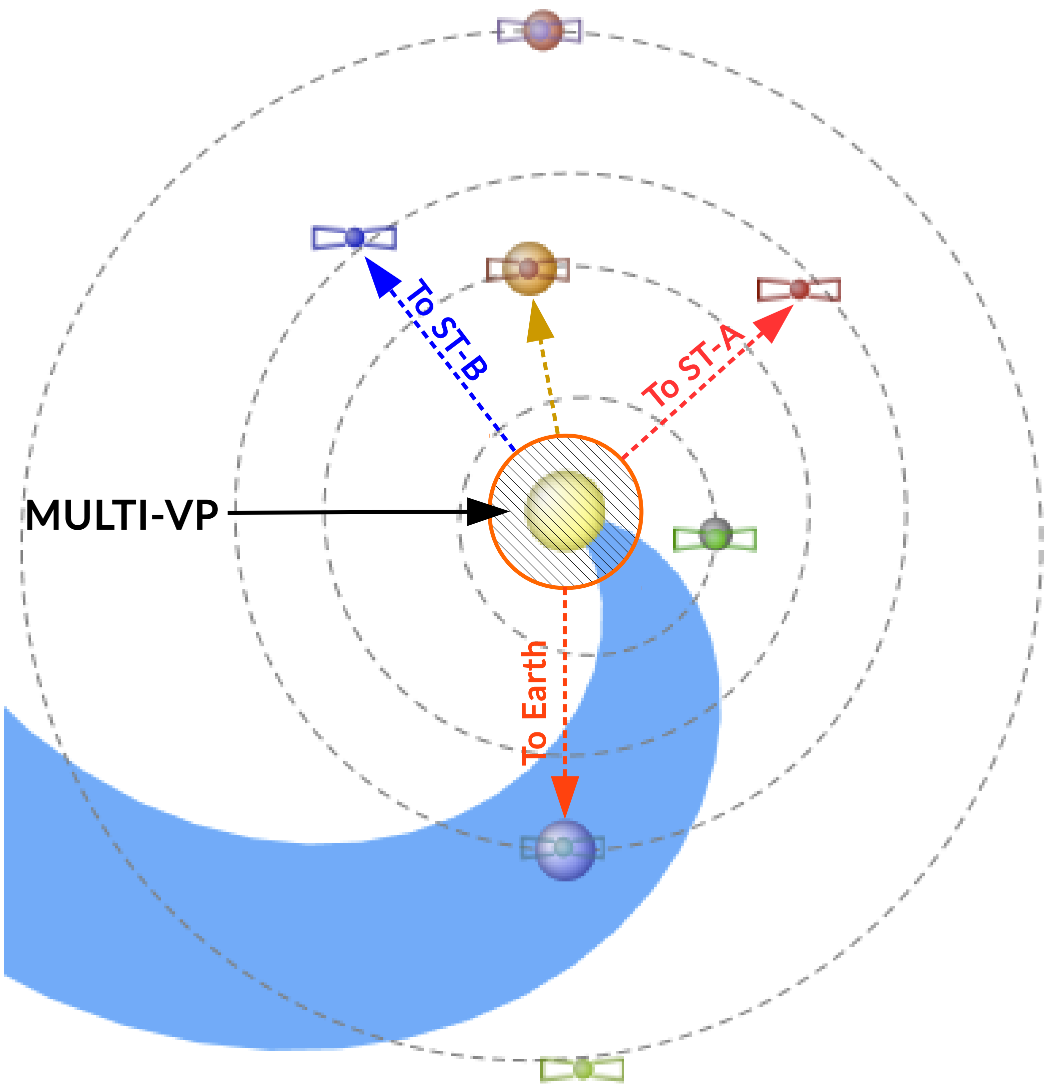
http://stormsweb.irap.omp.eu

WIP: SWiFT with 1D propagation

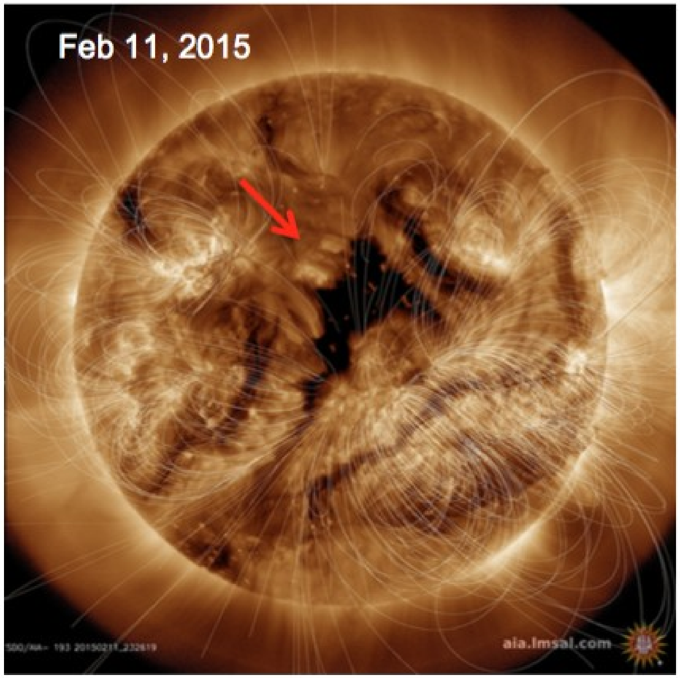


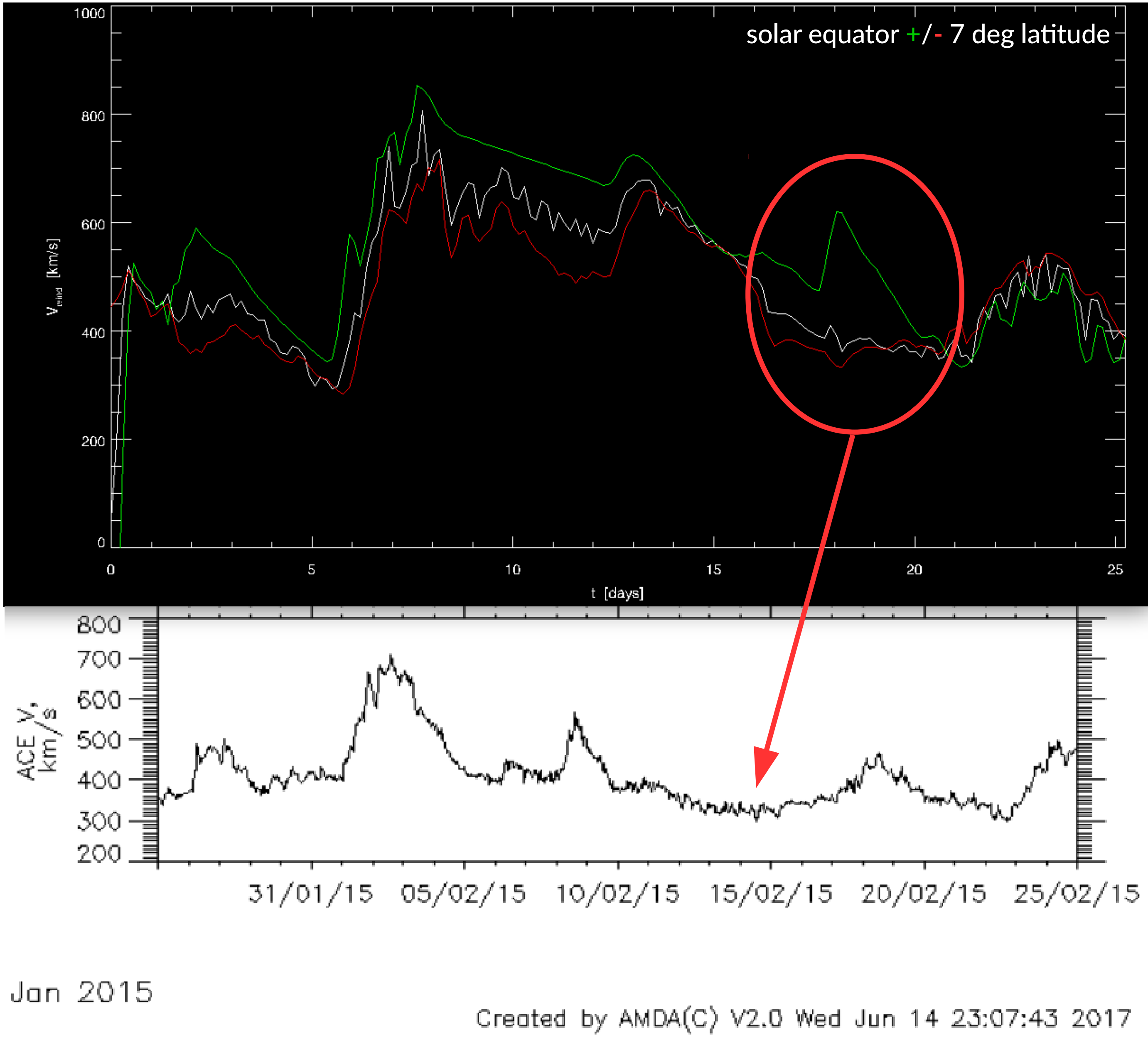
1D Propagation
(MULTI-VP + Tao's SW model)

- Forward propagation from output of MULTI-VP
- arbitrary radial paths
- each ray is independent (no azimuthal replication)
- off-ecliptic propagation
- time-series built from orbital position, rotation + background field evolution

WIP: SWiFT with 1D propagation

Effect of latitudinal mismatch
of starting point for propagation

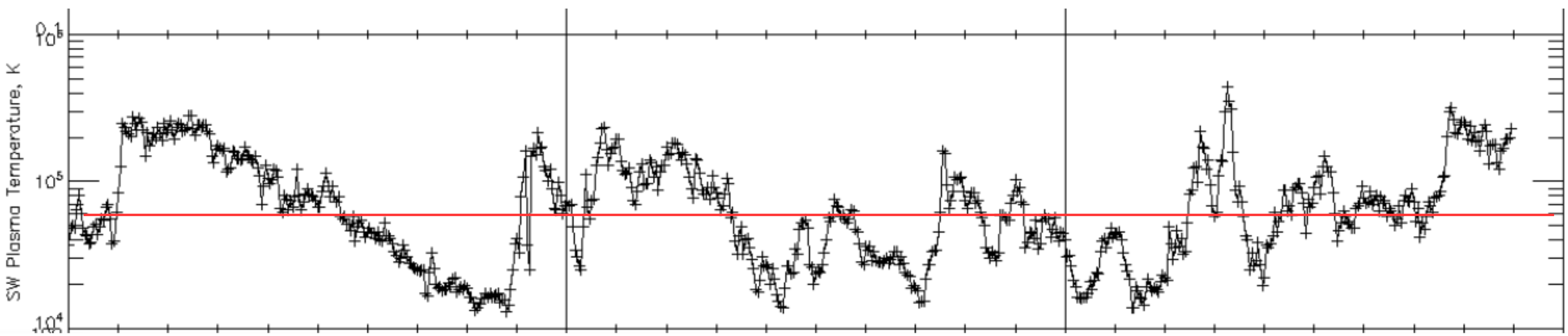




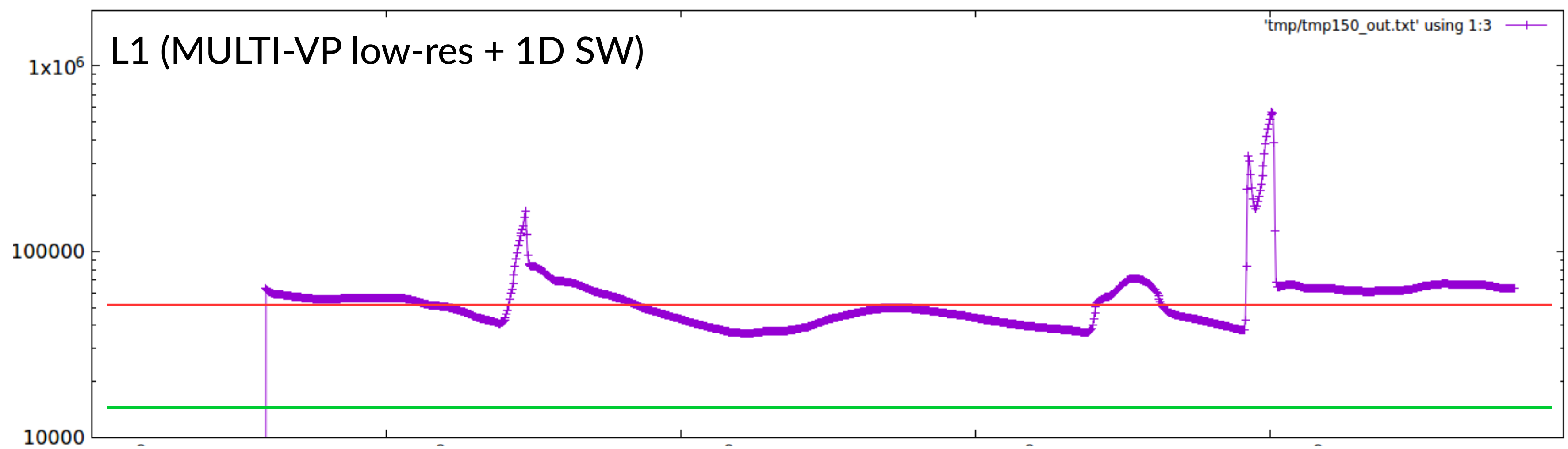
WIP: SWiFT with 1D propagation

Solar wind temperature

L1 (ACE)



<T>$_{ACE}$

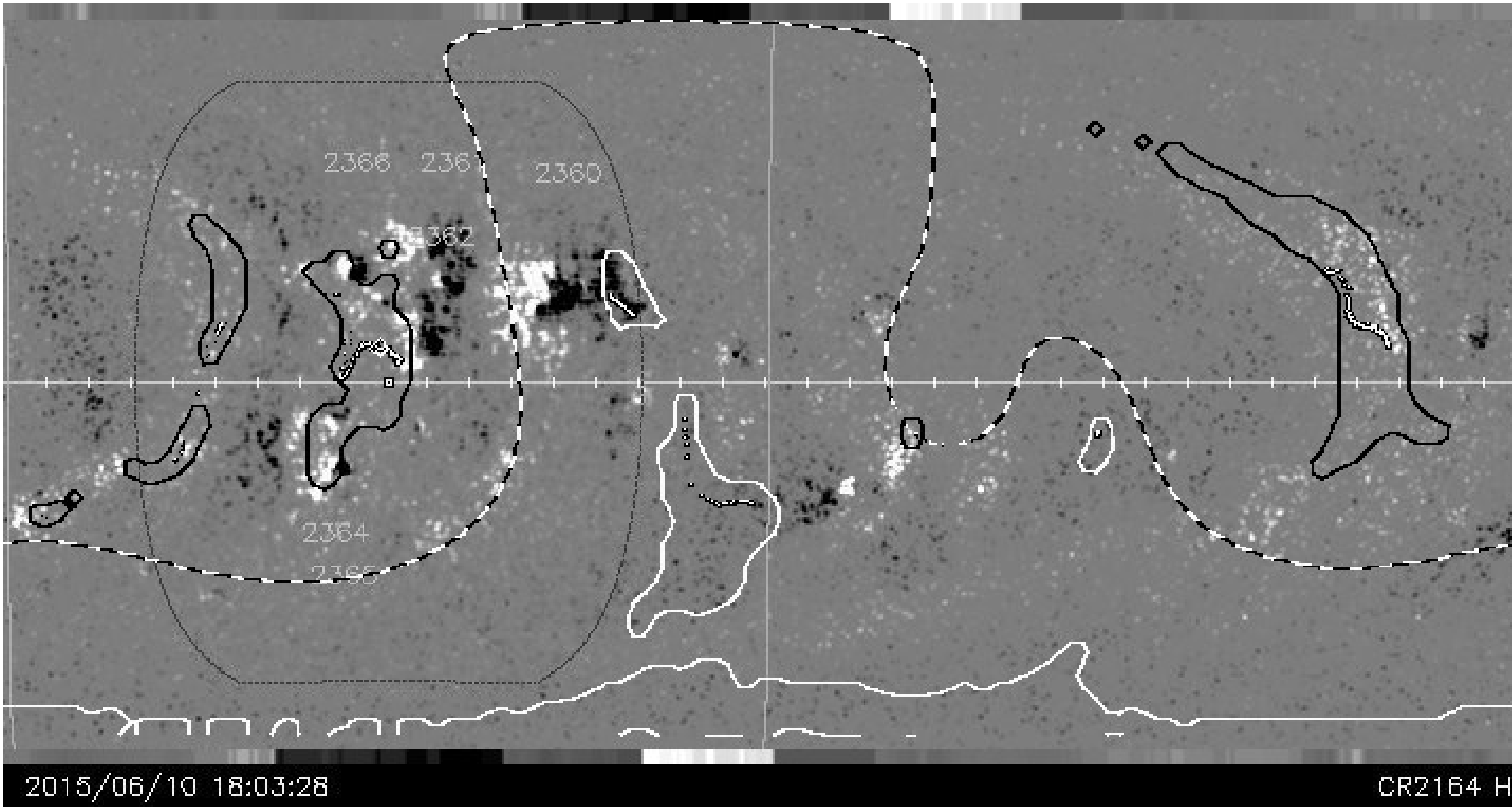


<T>$_{MVP+SW1D}$

<T>$_{ENLIL}$

WIP: Synchronic magnetograms

Forecasting surface magnetic fields



Synchronic magnetograms, data assimilation (SDO)

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Conclusions

SWiFT/ MULTI-VP: global wind model (1 - 32 R_{sun}), fast computation, alternative to semi-empirical (WSA) and full 3D MHD models

Full set of background solar wind properties, at all latitudes and azimuths

Synthetic diagnostics (e.g white-light, EUV, in-situ)

Corona to Heliosphere:

full 3D (ENLIL, EUFHORIA; CPU heavy, run-on-request)
1D SW (Tao's model; fast computing, real-time possible)

WIP: Forecast using data assimilation techniques,
Arbitrary 1D propagation paths

Perspectives: Space Weather, Solar Orbiter, Parker Solar Probe

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